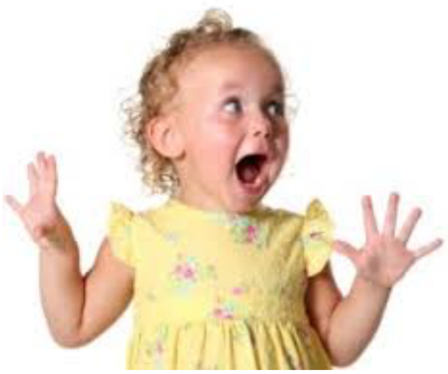
Proposal of New BSM Searches at the LHC and Belle-II

Filippo Sala

DESY Hamburg

BSM at the LHC?



2010

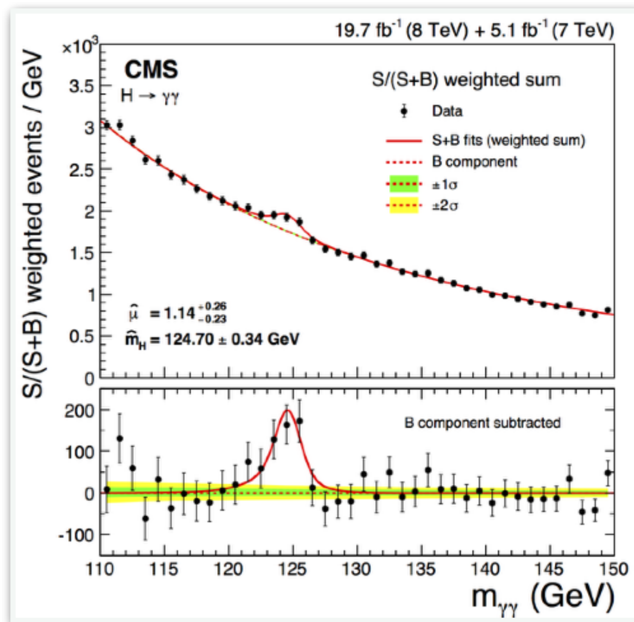
2012

2018

Bound

Exclusion

…



It's Standard Model

Limit

No New Physics
at these energies

…

?

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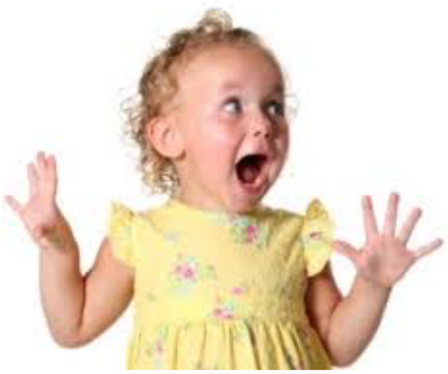

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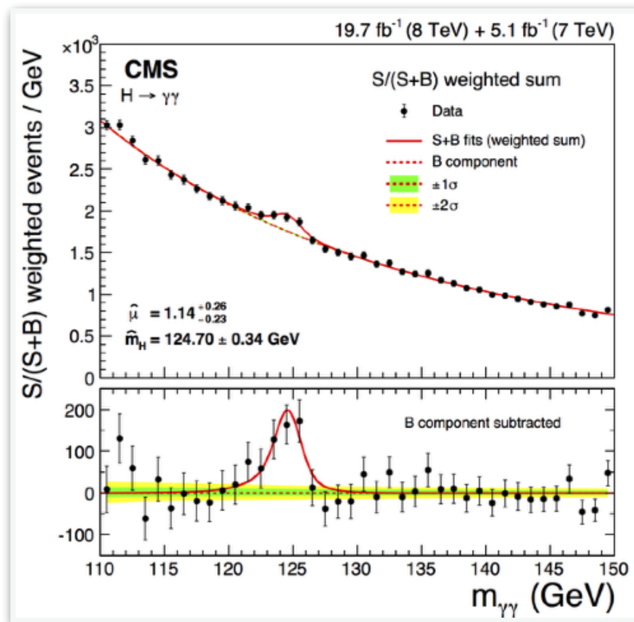

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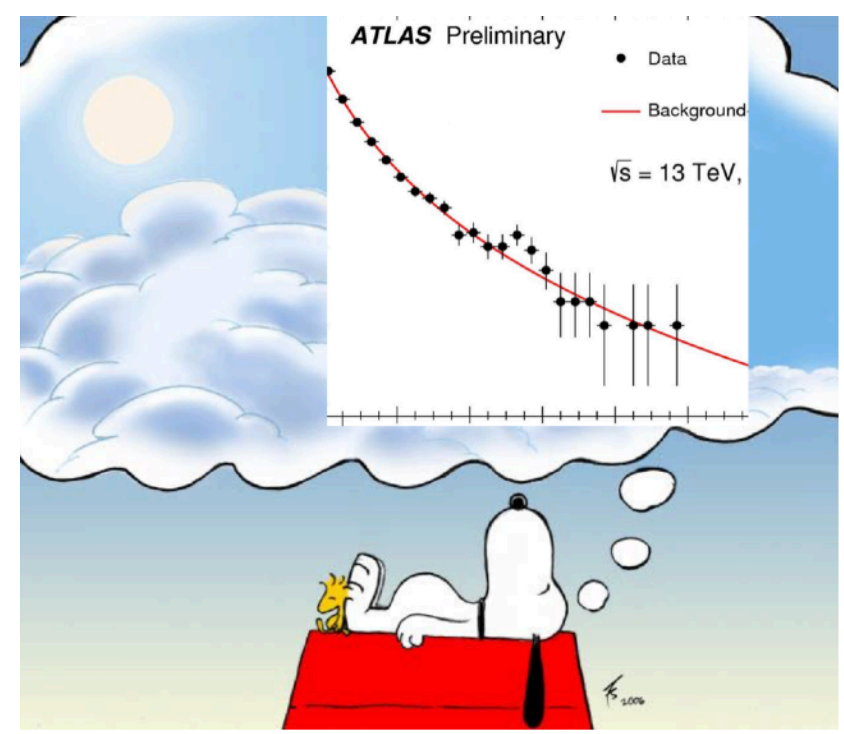
(Most?) **Solid discovery method** at colliders

Look for peaks in invariant mass distributions

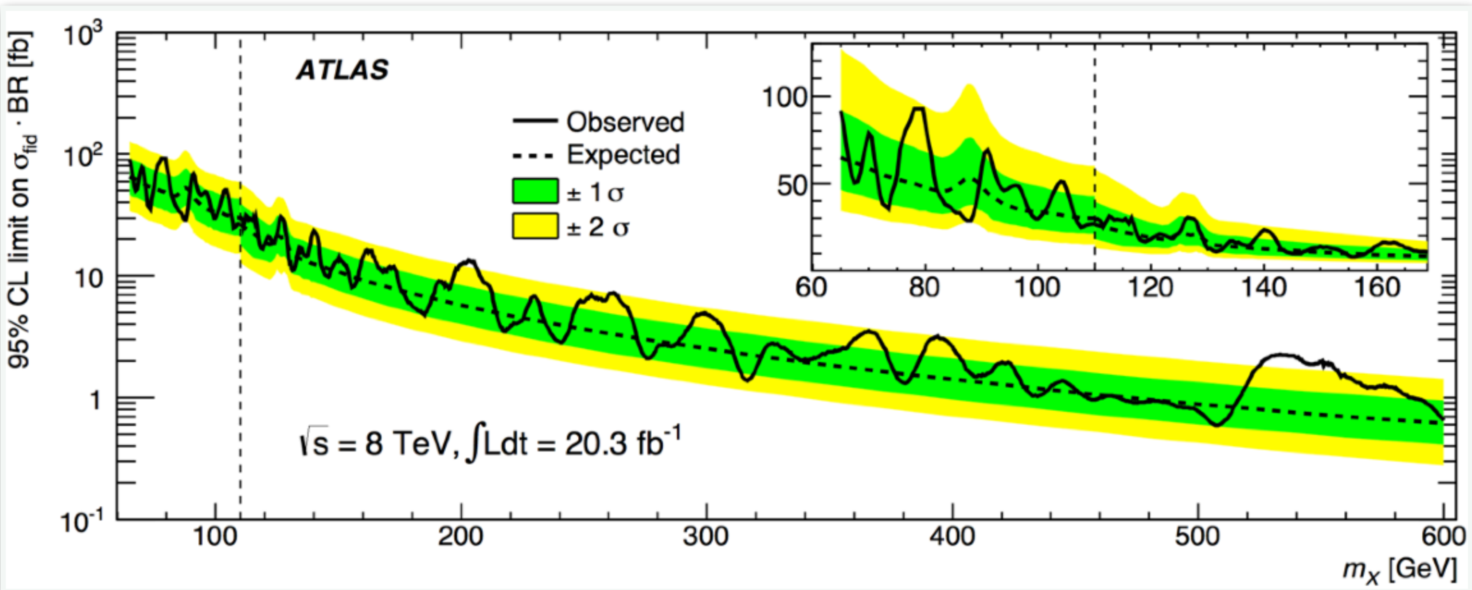
Diphotons **Dijets** **Dibosons (W,Z)**

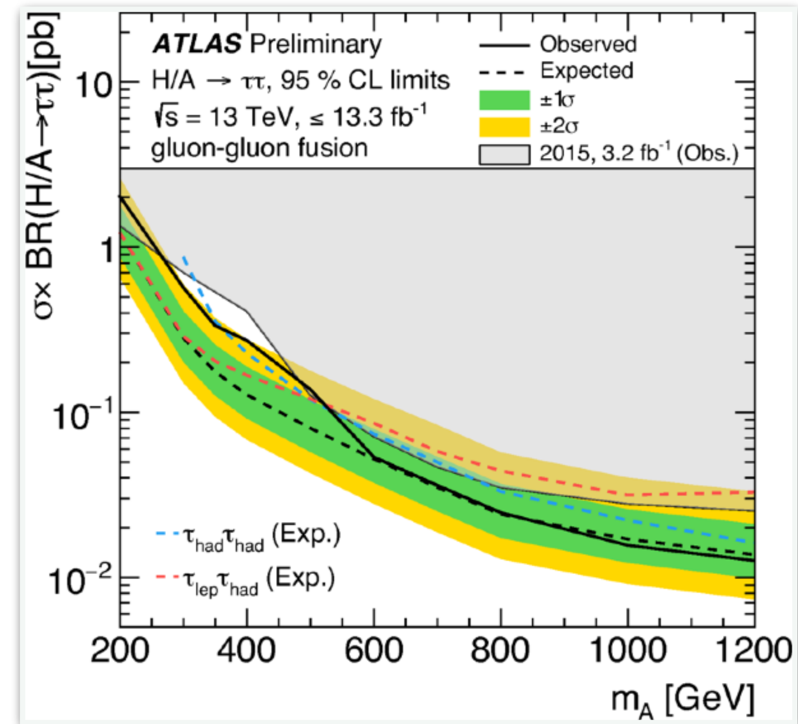
Dileptons **Ditop** **DiHiggs**



BSM resonances: where to look?

Present searches: $M_{\gamma\gamma,\tau\tau,\dots} > O(100)\ \text{GeV}$





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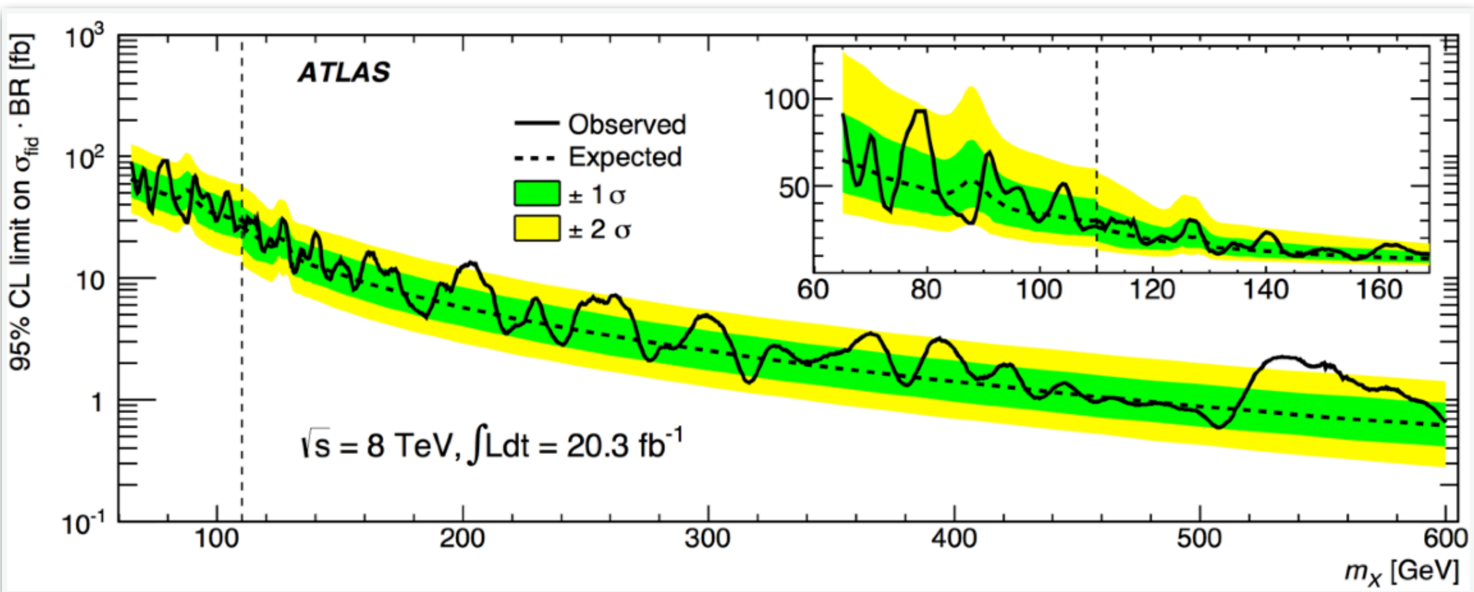

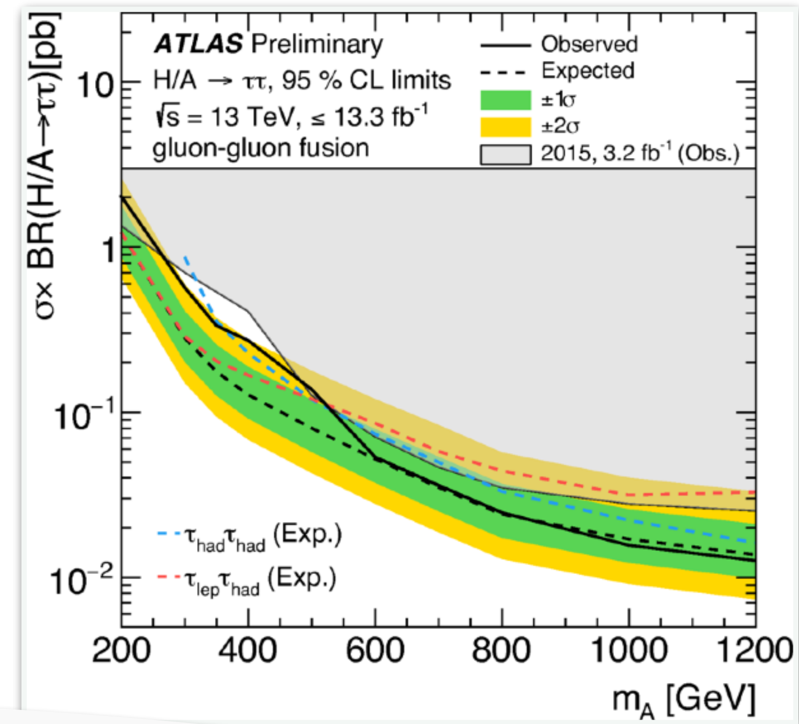

Why not $M_X < O(100)\ \mathrm{GeV}$?

1. Theory bias towards high masses
2. "Low-mass already constrained by previous colliders (LEP,…)"
3. "It is very difficult!" Minimal pT cuts, …

Here: demystify 1. 2. and 3., **new limits** and prospects at LHC

1. Theory bias towards high masses

Why not $M_X < O(100)$ GeV ?

Why low-mass resonances?

LHC is pushing **solutions to SM problems** (hierarchy, flavour, …) to $M_{\rm BSM}$ **>> TeV**

Richer sectors could exist there **How to test them?**

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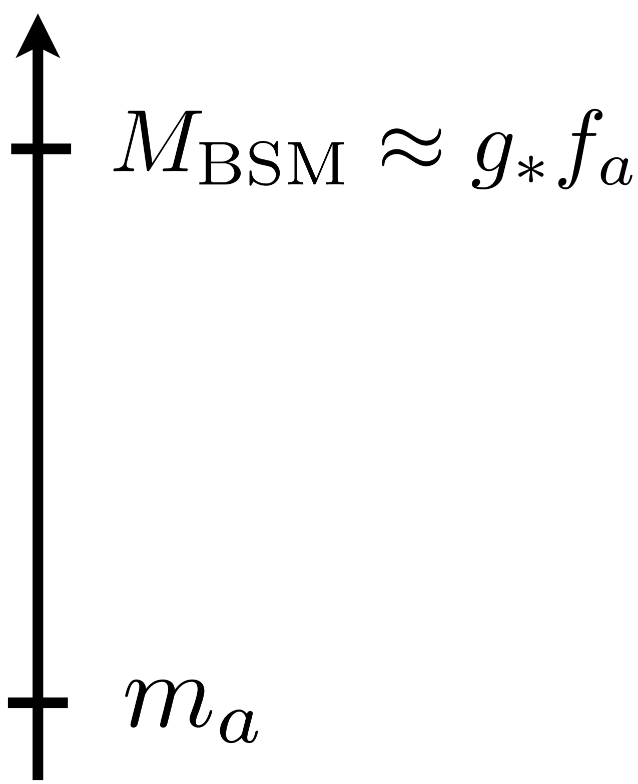
via ALPs!



aka Pseudo Goldstone Bosons (**PGB**s)

from spontaneous breaking of global symmetry

with a small explicit breaking that controls $m_a \neq 0$

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$M_{\rm BSM} \approx g_* f_a$

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m_a **Mass** of the ALP naturally lighter than any BSM scale $M_{\rm BSM}$

(*technically natural*, unlike Higgs mass)

f_a decay constant controls ALP **Couplings**

e.g. $\mathcal{L}_{\rm int} = \frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$

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$M_{\rm BSM} \approx g_* f_a \gtrsim \text{TeV}$ ~ from LHC exclusions

…osons (**PGB**s)

from spontaneous breaking of global symmetry

with a small explicit breaking that controls $m_a \neq 0$

$m_a \sim 1 - 100 \text{ GeV}$ ~ an unexplored range

…BSM scale $M_{\rm BSM}$

(*technically natural*, unlike Higgs mass)

$f_a \sim 0.1 - 100 \text{ TeV}$ of interest for colliders (see rest of talk)

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ALPs and BSM: strongly coupled

They already exist: pions from QCD

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"**Just because**" strong sector: vector-like confinement see e.g. Kilic Okui Sundrum 0906.0577

[add gauge group that confines at $\gtrsim$TeV, w/new fermions, vector-like to satisfy EW precision tests]

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Natural strong sector: composite Higgs models

Example: SO(6)/SO(5) has 5 PGB, the Higgs and a singlet η — see e.g. Gripaios+ 0902.1483, Redi Tesi 1205.0232

No tuning in η potential $\Rightarrow \quad m_\eta \sim m_h \times \frac{f}{v} \sim 600 \text{ GeV} \times \sqrt{\frac{0.05}{(v/f)^2}}$

with dependence on top representation

e.g. if only bottom contributes: $m_\eta \sim 10 \text{ GeV} \times \sqrt{\frac{0.05}{(v/f)^2}}$

Larger coset structures have more PGBs

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Larger coset structures have more PGBs

Less natural composite Higgs models:

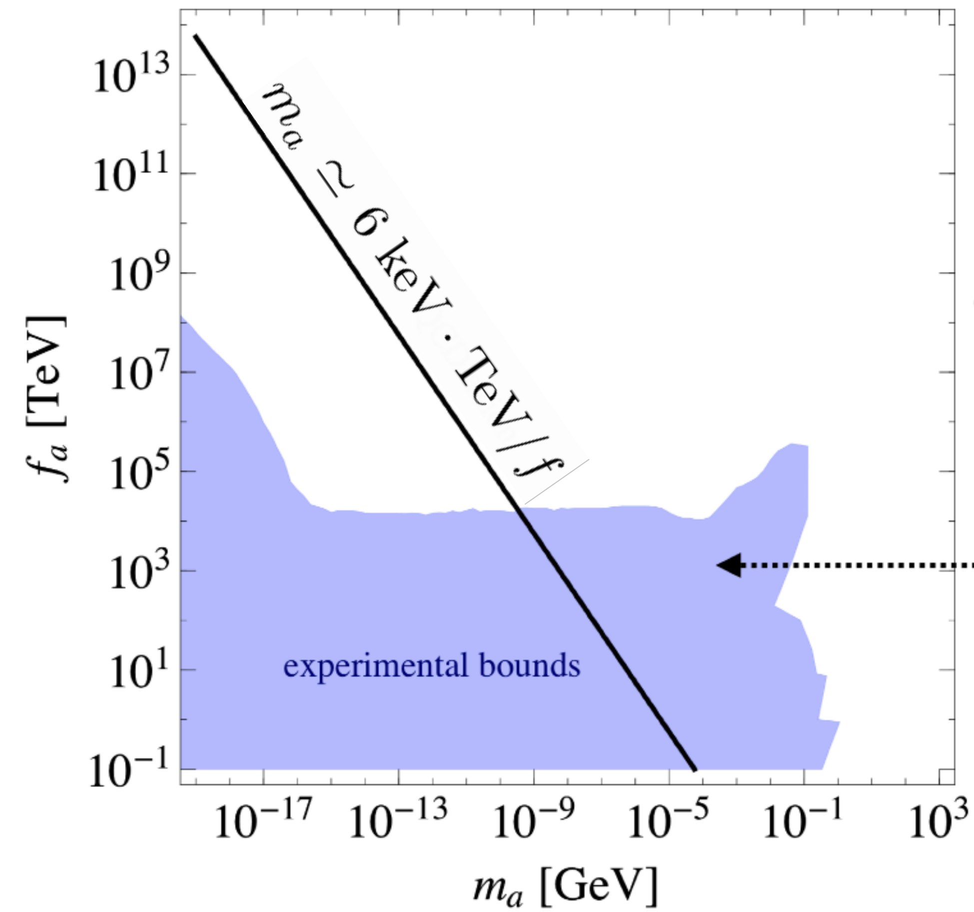
give up on little hierarchy and focus on

- DM & GUT — Bernard+ 1409.7391
- generate EW & DM scales — Antipin+1410.1817
- ....

ALPs and BSM: QCD axion

Standard QCD axion points to large f_a and small m_a

$$V_a \simeq -\Lambda_{\rm QCD}^4 \cos\frac{Na}{f}$$



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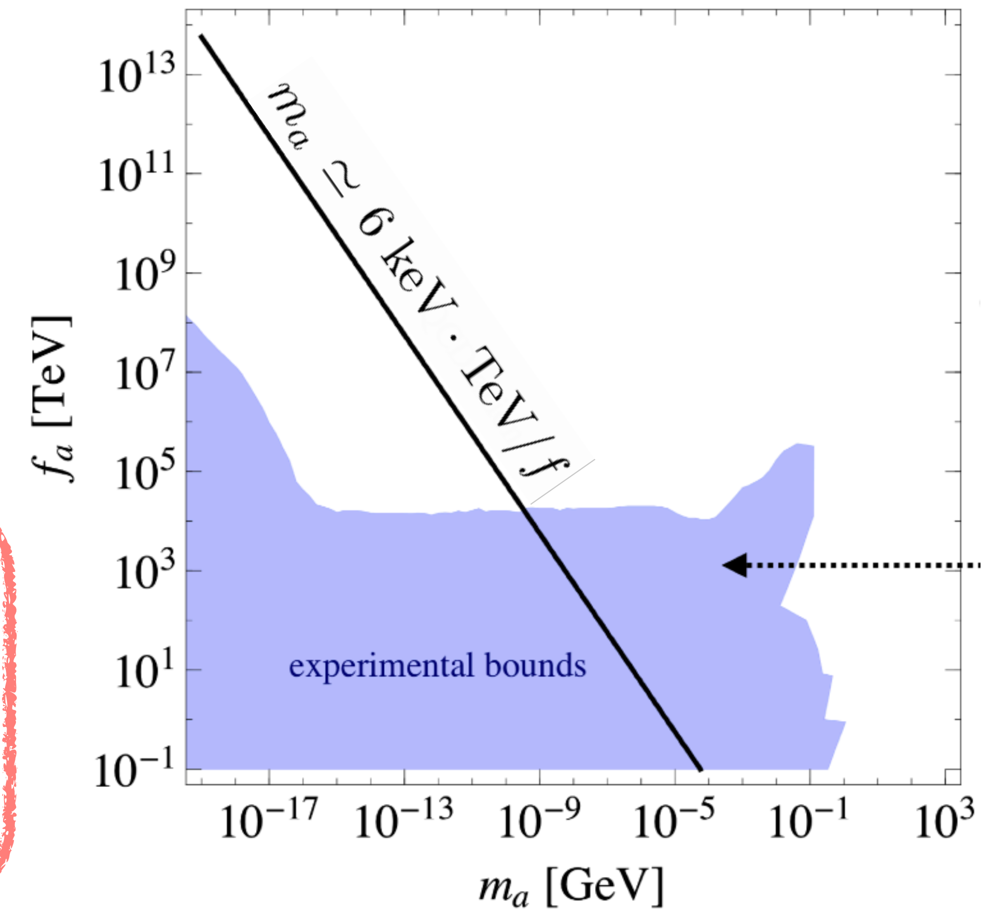
but: **"Axion Quality" problem** spoils solution to strong CP

$$\Delta V_{P\!\!\!/Q} = \lambda_\Delta \frac{\Phi^\Delta}{\Lambda_{\rm UV}^{\Delta-4}} + {\rm h.c.} \qquad \Phi = \frac{f_a}{\sqrt{2}} e^{ia/f_a}$$

Kamionkowski March-Russel hep-th/9202003,…



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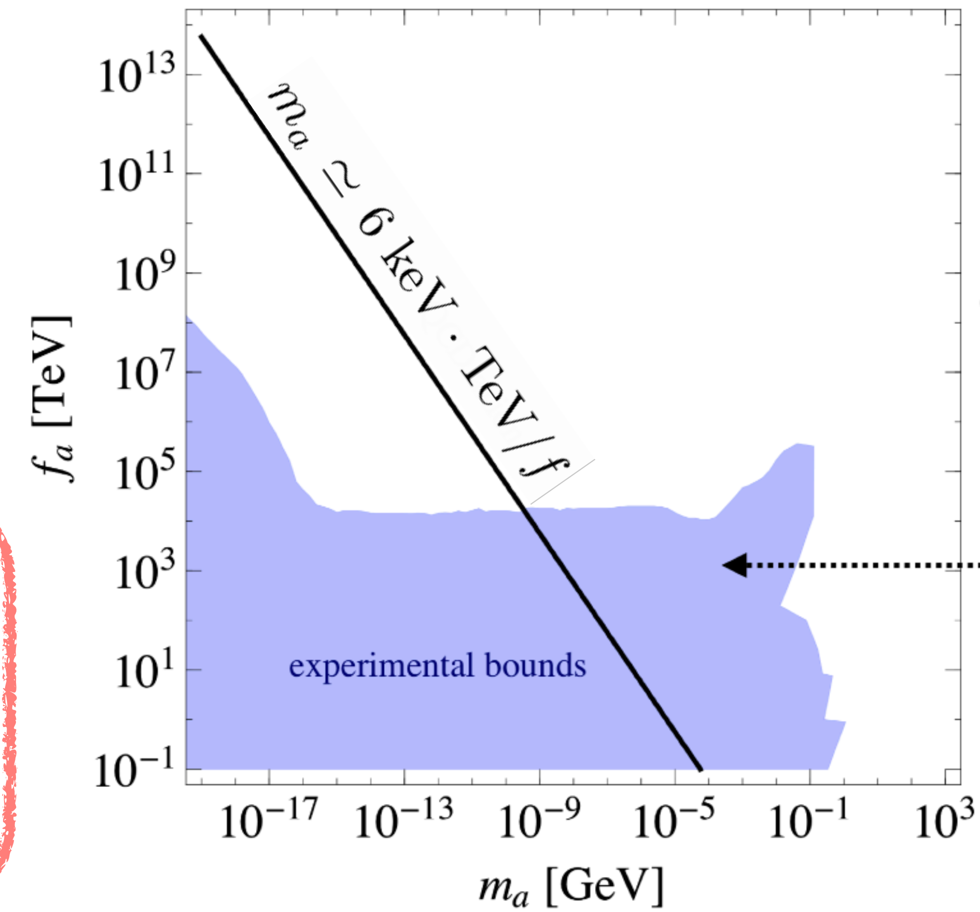

Example: $\Delta = 6$ (same of SM baryon number)

$$\Lambda_{\rm UV} = M_{\rm Pl} \Rightarrow f \lesssim O(10)\ {\rm TeV}$$

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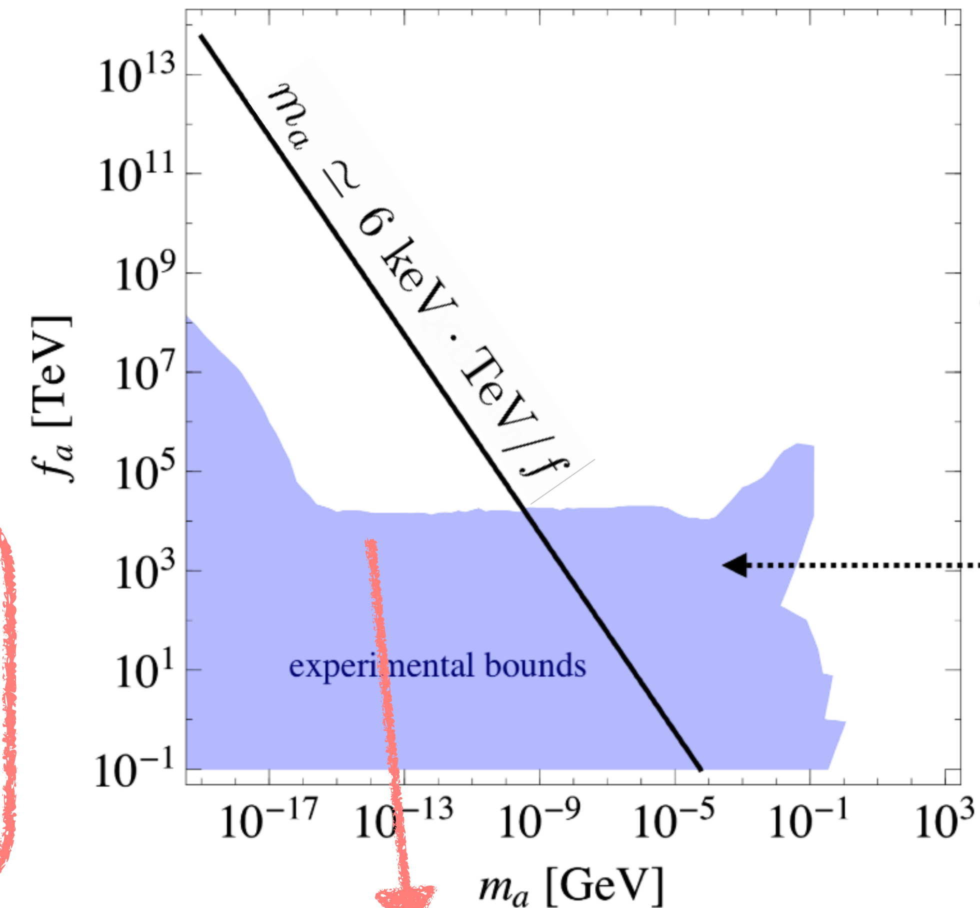

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1. Push Δ to much larger values

   … Redi Sato 1602.05427
   Duerr+ 1712.01841

2. Model building for smaller f_a and larger m_a

   Rubakov hep-ph/9703409 ……
   M.K Gaillard+ 1805.06465

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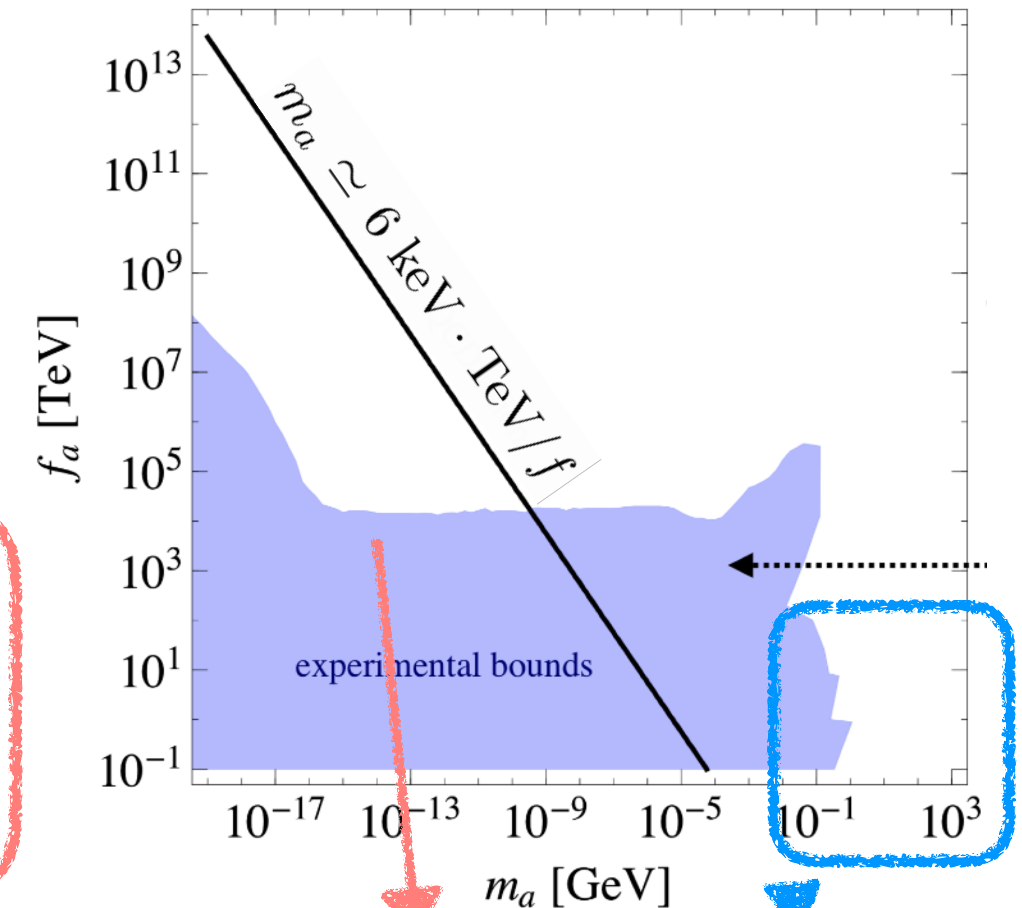

strong CP solved here!

2. Model building for smaller f_a and larger m_a

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ALPs and BSM: Dark Matter

Pseudoscalar-mediated Dark Matter $\mathcal{L}_{\rm int} = \frac{a}{4\pi f_a} \alpha_s c_3 G\tilde{G} + g_* \Phi \psi \tilde{\psi}$

$$\Phi = \frac{f_a}{\sqrt{2}} e^{ia/f_a}$$

$$m_\psi = g_* f/\sqrt{2}$$

Observed relic abundance for $m_\psi \simeq 4.6 \text{ TeV} \frac{c_3}{10} \left(\frac{g_*}{3}\right)^2 \Rightarrow f \simeq 1.9 \text{ TeV} \frac{3}{g_*}$

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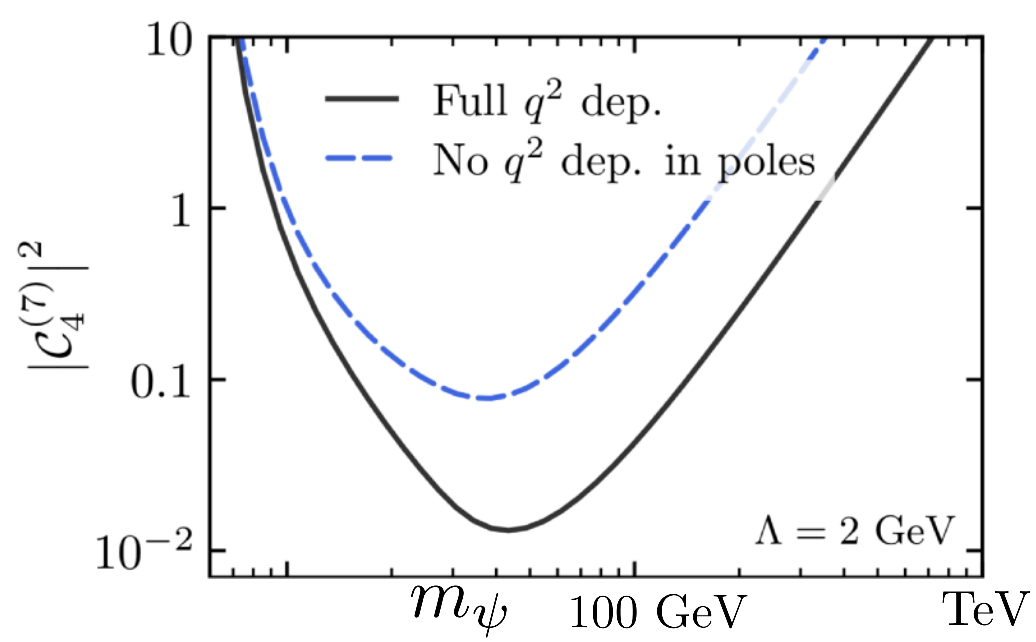
Direct Detection completely irrelevant →

Indirect Detection not yet competitive

(caveat: should compute Sommerfeld)

Colliders are needed to test this scenario!

Bishara+ 1707.06998



$$\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi} i\gamma_5 \chi) G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$

ALPs and BSM: SUSY R-axion I

N = 1 SUSY always accompanied by a continuous $U(1)_R$ = "R-symmetry"

$$R: \; \theta_\alpha \to e^{i\epsilon}\,\theta_\alpha \qquad [R, Q] = -Q$$

R-charge assignments: $\Phi = \phi + \sqrt{2}\theta\,\psi + \theta^2\, F$

$$r_\phi = r_\Phi$$
$$r_\psi = r_\Phi - 1$$
$$r_F = r_\Phi - 2$$

Vector superfields are real $\Rightarrow$ gauginos have $r_\lambda = 1$

Lagrangian $\mathcal{L}$ R-symmetric $\Rightarrow R(W) = 2$

($\Leftarrow$ if Kahler canonical)

$$\mathcal{L} \supset \int d^2\theta\, W \; + \text{c.c.}$$

W superpotential

ALPs and BSM: SUSY R-axion II

Nelson-Seiberg NPB416 (1994)

i) SUSY broken in global minimum

ii) superpotential W "generic"
(i.e. contains all terms not forbidden by symmetries)

$\Longrightarrow$ Lagrangian respects a $U(1)_R$

$U(1)_R$ needs to be broken because of

gaugino masses

$\mathcal{L} \supset m_\lambda \, \lambda\lambda \quad [r_\lambda = 1]$

EW symmetry breaking & Higgsino masses

$\mathcal{L} \supset B_\mu \, H_u H_d + \text{c.c.}$ & $W \supset \mu \, H_u H_d$

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Massless Goldstone in the spectrum R-axion a

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→ Tune CC to zero: explicit breaking of $U(1)_R$

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Bagger+ hep-ph/9405345

→ Metastable vacuum Intriligator Seiberg Shih 2007

....

→ $m_a \ll M_{\text{SUSY}}$

light SUSY particle by symmetry

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light SUSY particle by symmetry

Could be first sign of SUSY at colliders!

Bellazzini Mariotti Redigolo FS Serra 1702.02152

R-axion- as Dark Matter mediator

Spectrum à la gauge mediation

Gravitino DM $m_{3/2} = F/(\sqrt{3} M_{\rm Pl}) \simeq 11\ {\rm meV} \cdot (g_*/3) \cdot (f/4\ {\rm TeV})^2$

Cannot make observed DM for these values of parameter

(motivated by naturalness of Fermi scale)

Respects all bounds from cosmology and collider

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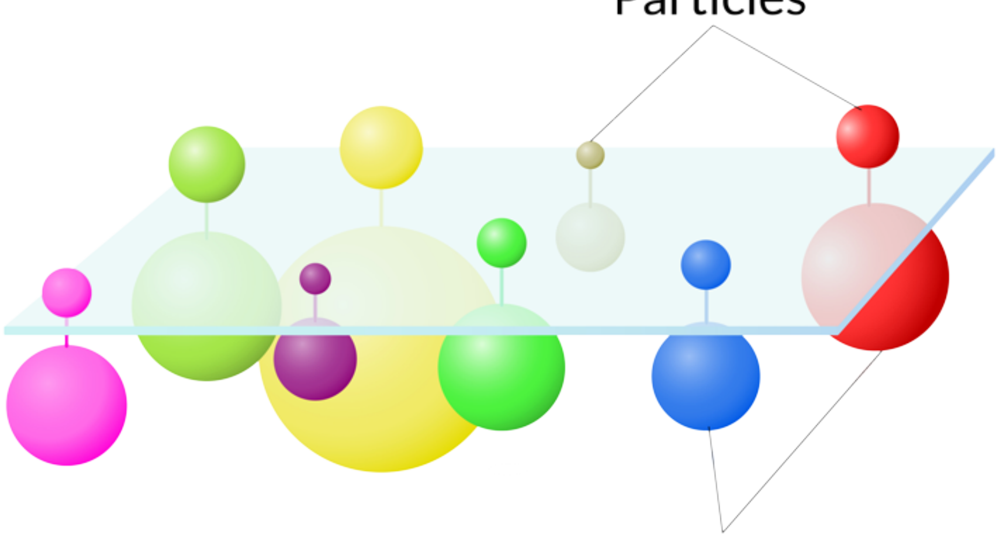

DM from messenger or SUSY breaking sectors

Dimopoulos Giudice Pomarol hep-ph/9607225

R-axion is natural portal! Mardon Nomura Thaler 0905.3749
Fan Thaler Wang 1004.0008

Motivated realisation of ALP-portal Dark Matter

Theory summary

Pseudo Goldstone bosons (ALPs) with

$$m_a \sim 1 - 100 \text{ GeV}$$
$$f_a \sim 0.1 - 100 \text{ TeV}$$

arise in several motivated models (**QCD axion**, **DM**, **SUSY**, **CHM**,…)

Pheno observation

Coupling to gluons $\sim aG\tilde{G}$ often neglected in ALPs pheno

but mandatory for **QCD axion**

natural in **CHM** (e.g. loops of tops, …)

as well as in **SUSY**! (e.g. loops of tops, gluinos, …)

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Present ALP mass coverage

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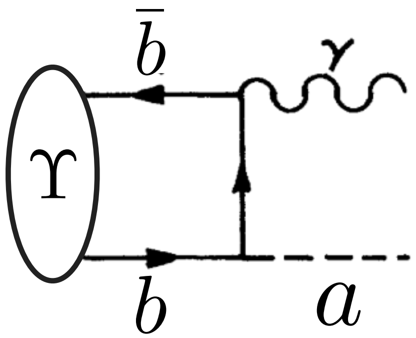

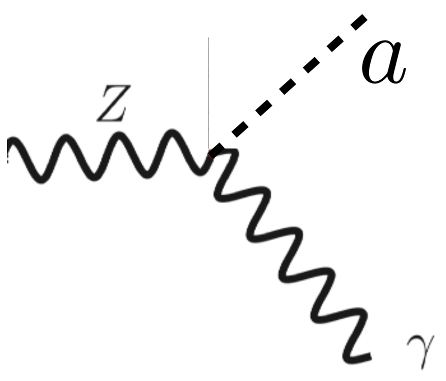

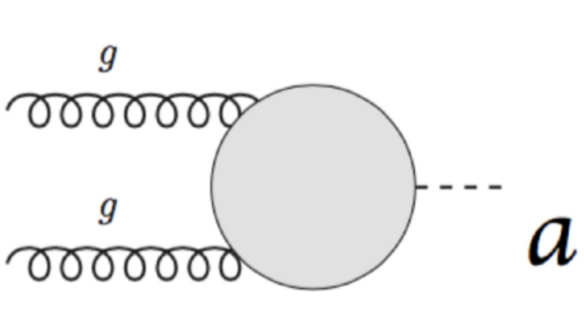

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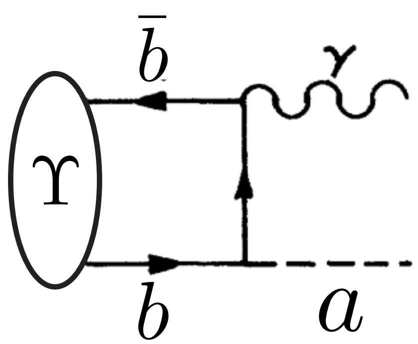

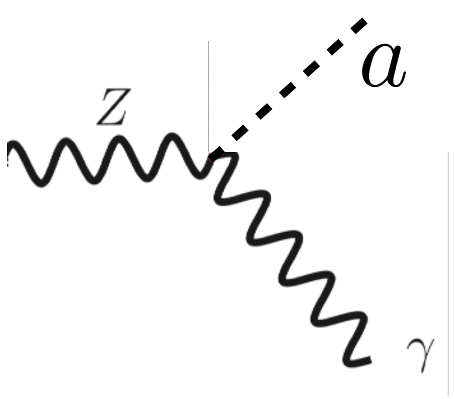

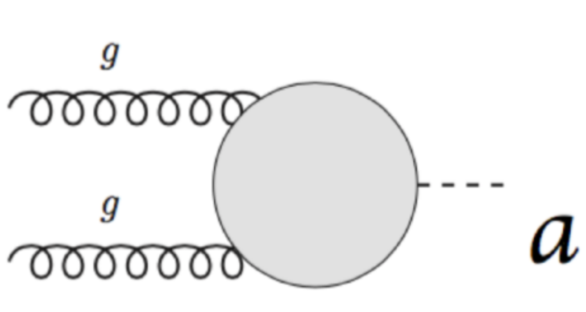

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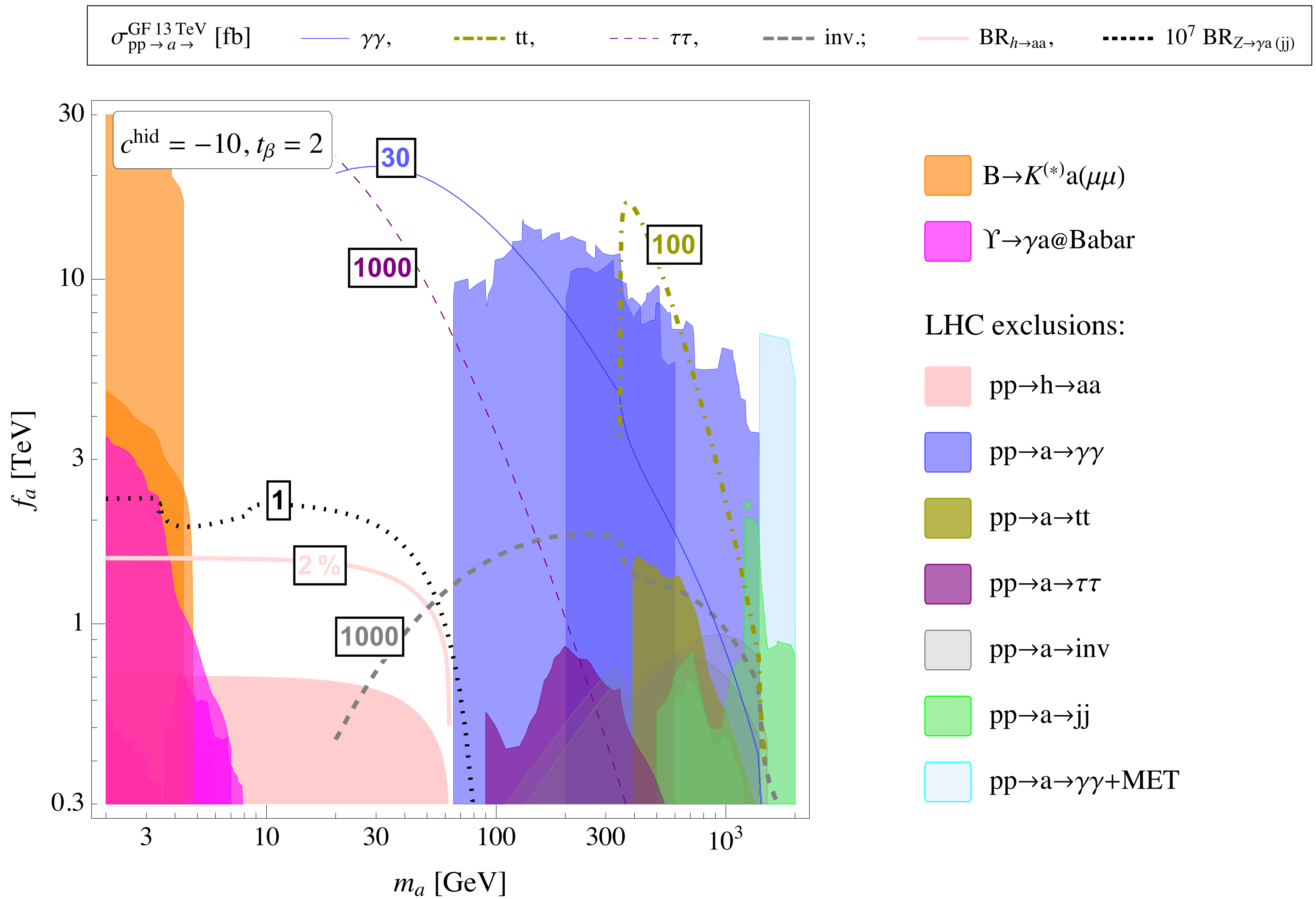

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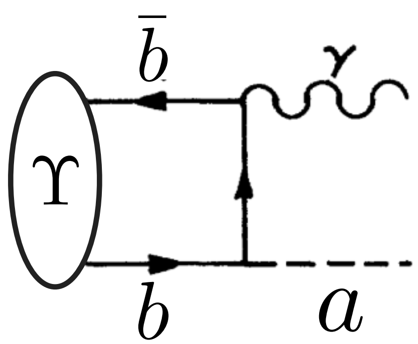

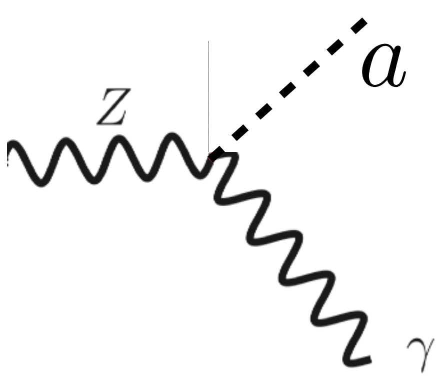

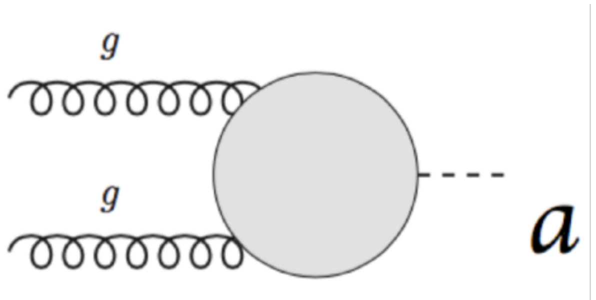

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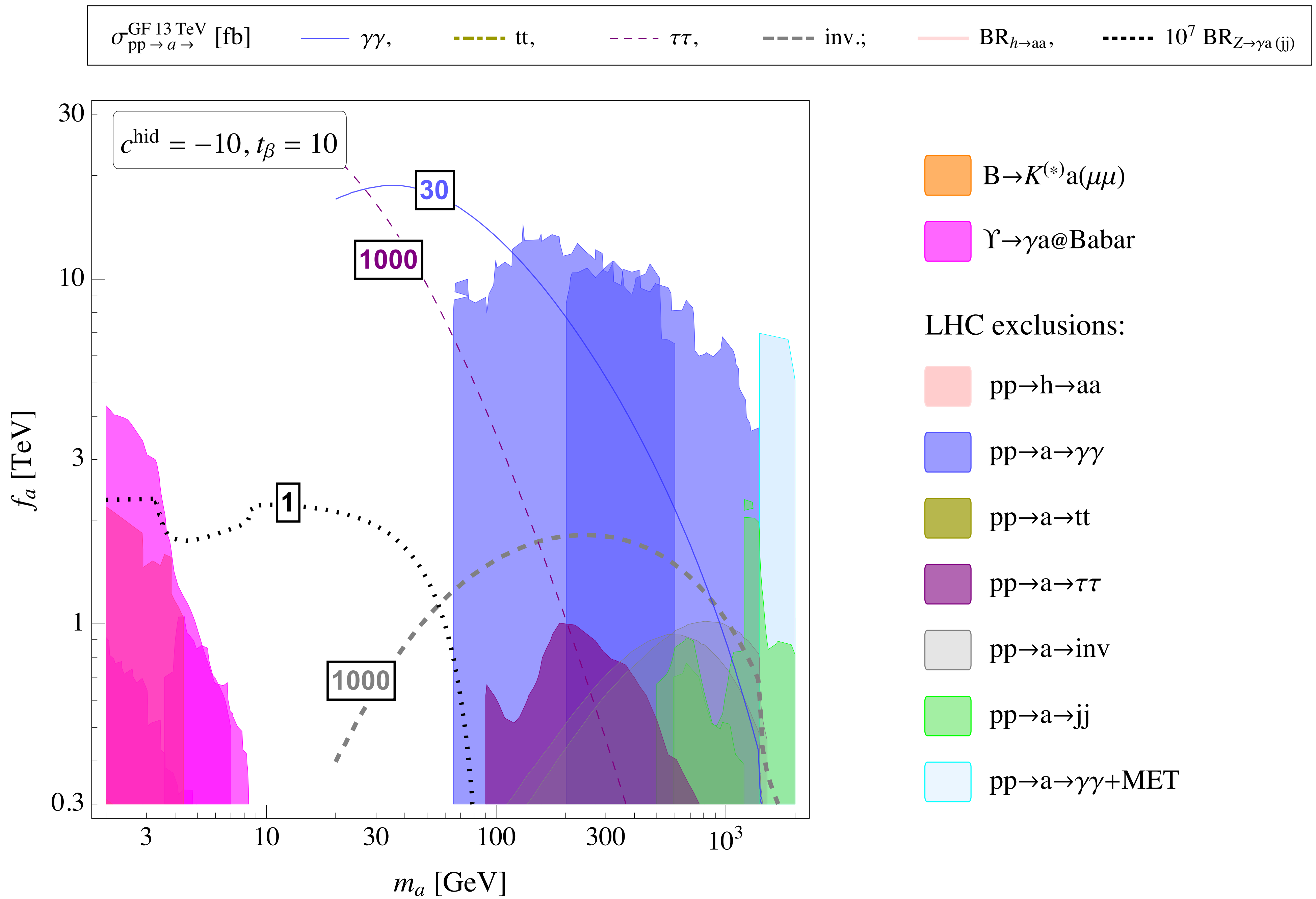

Bellazzini Mariotti Redigolo FS Serra 1702.02152

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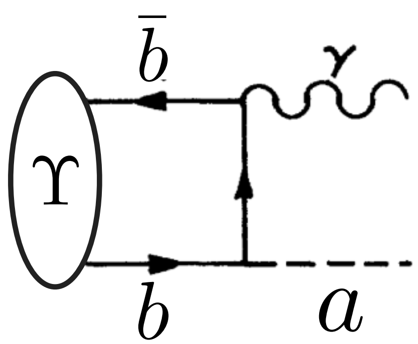
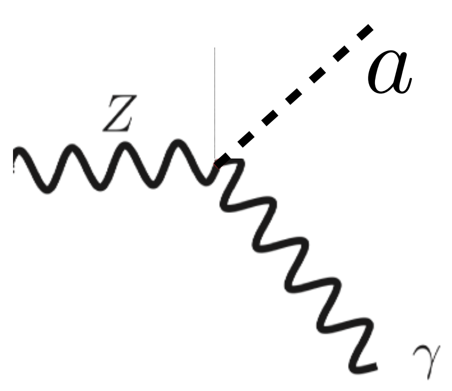
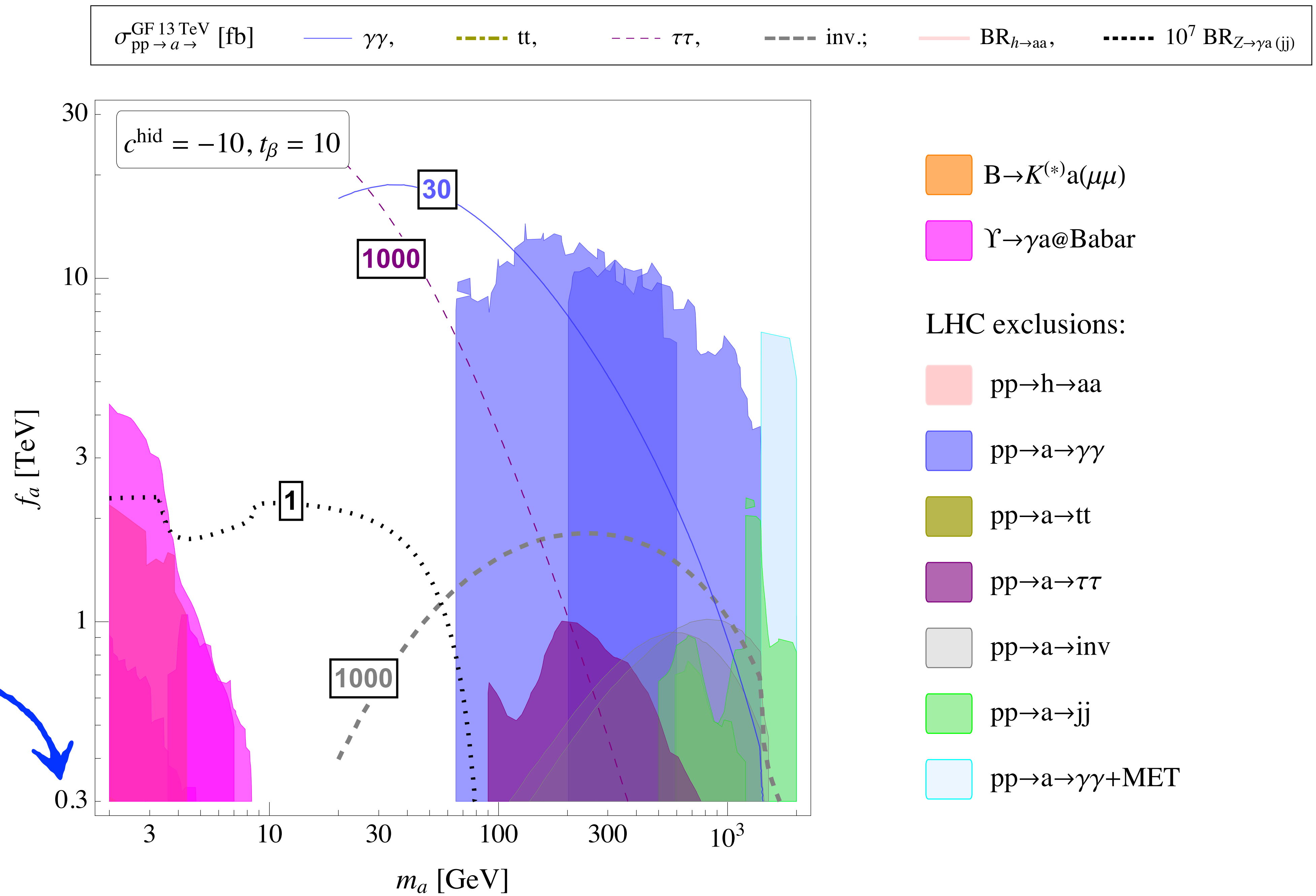




LEP only constrains smaller values of f_a

.....



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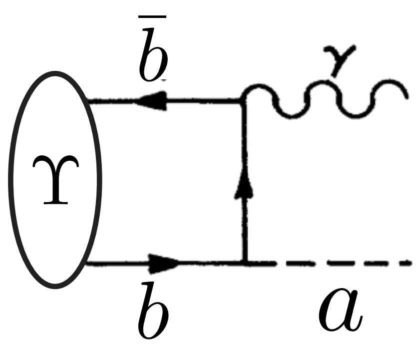

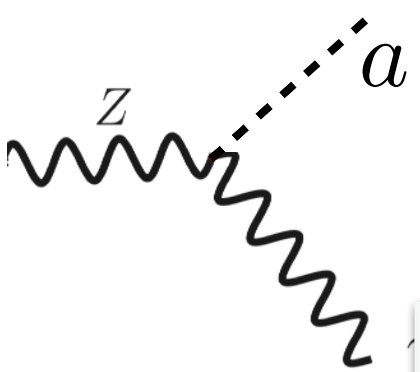

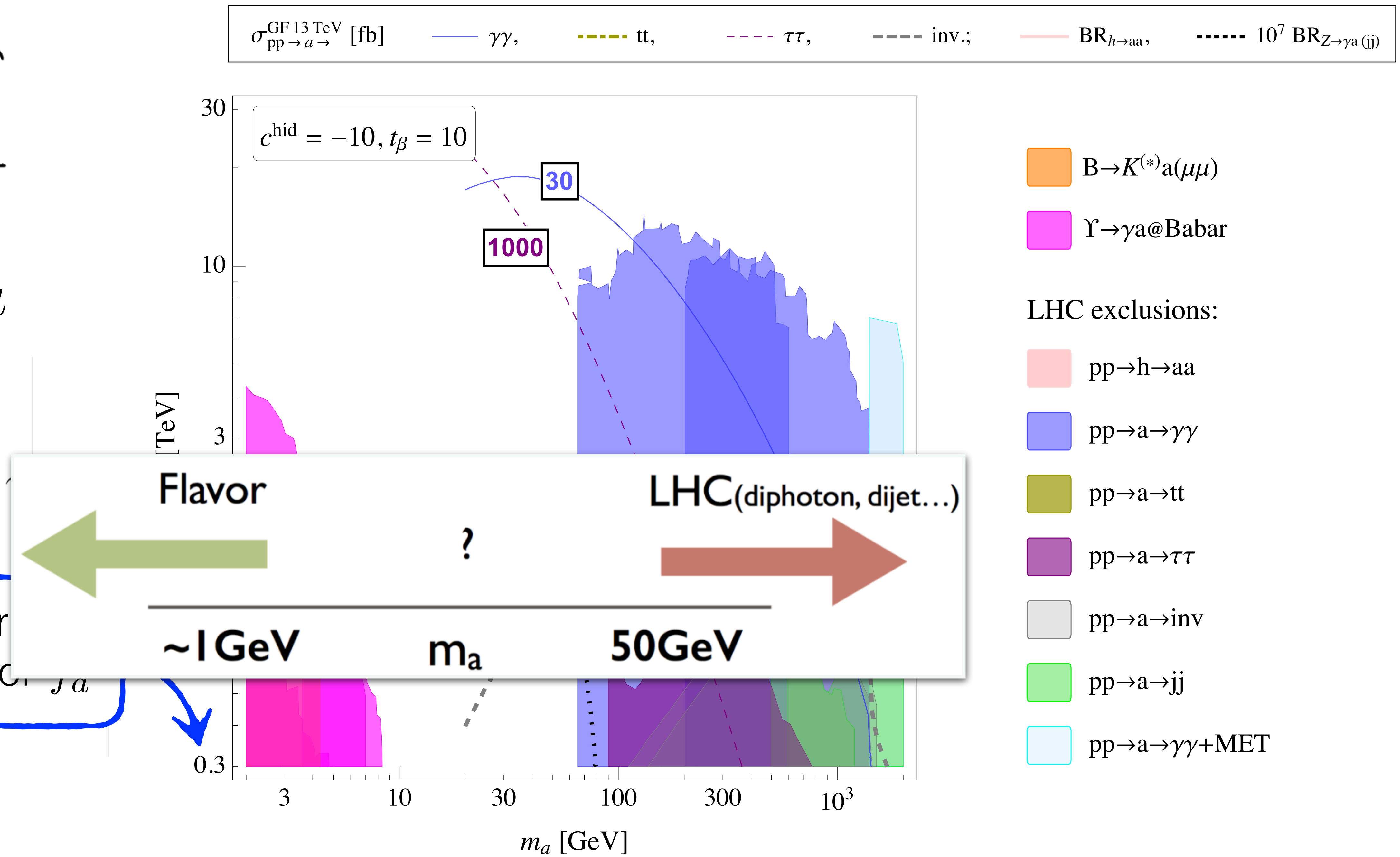

LEP only constr… smaller values of f_a

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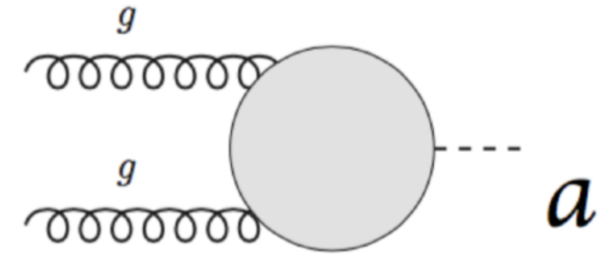
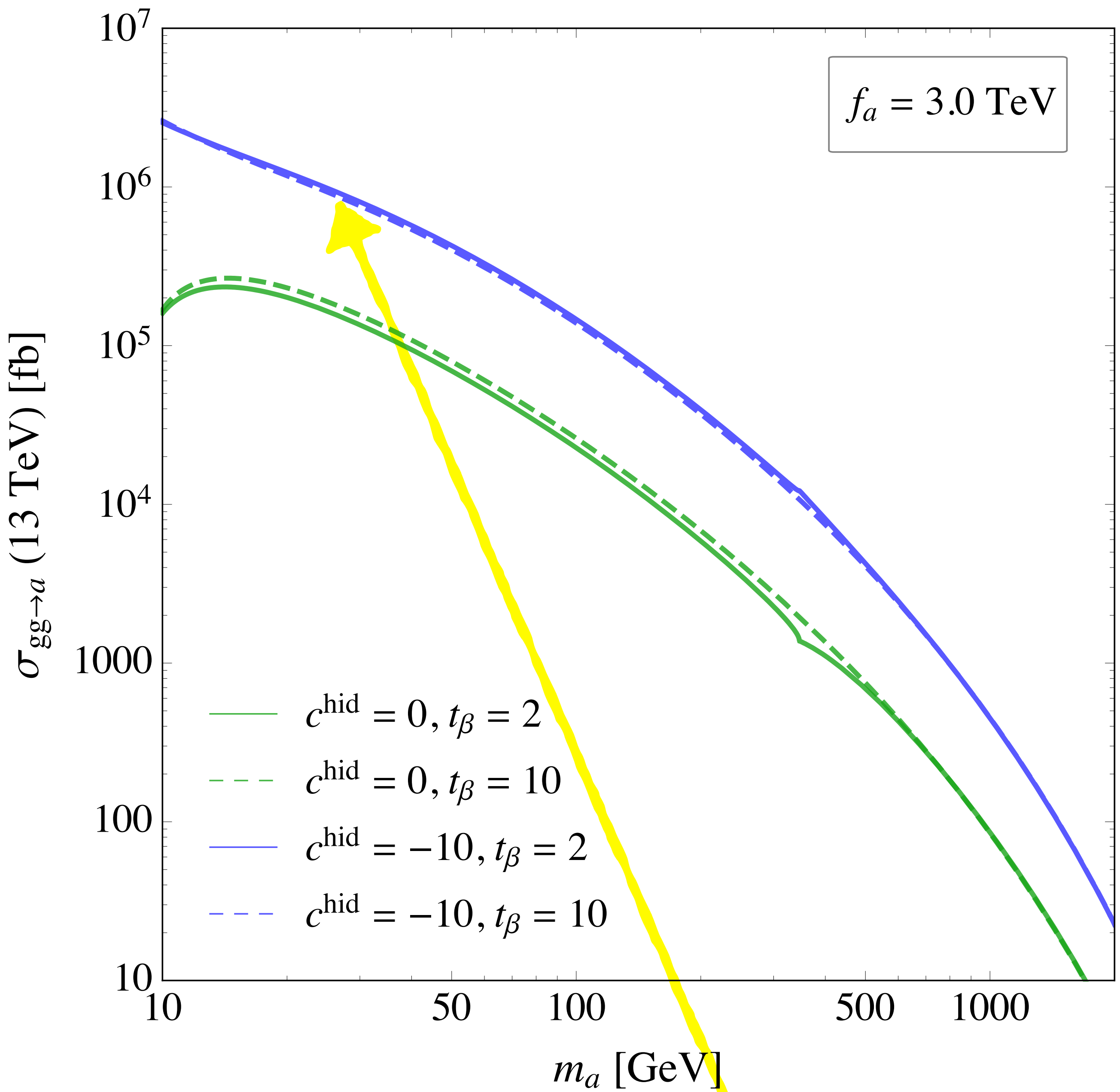
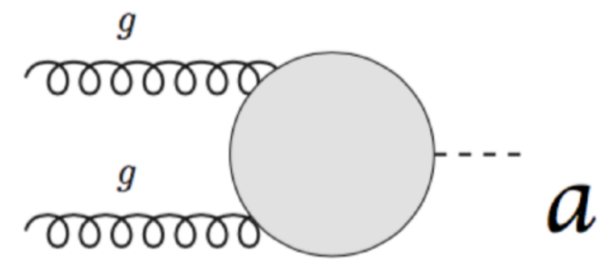
ALP production at the LHC

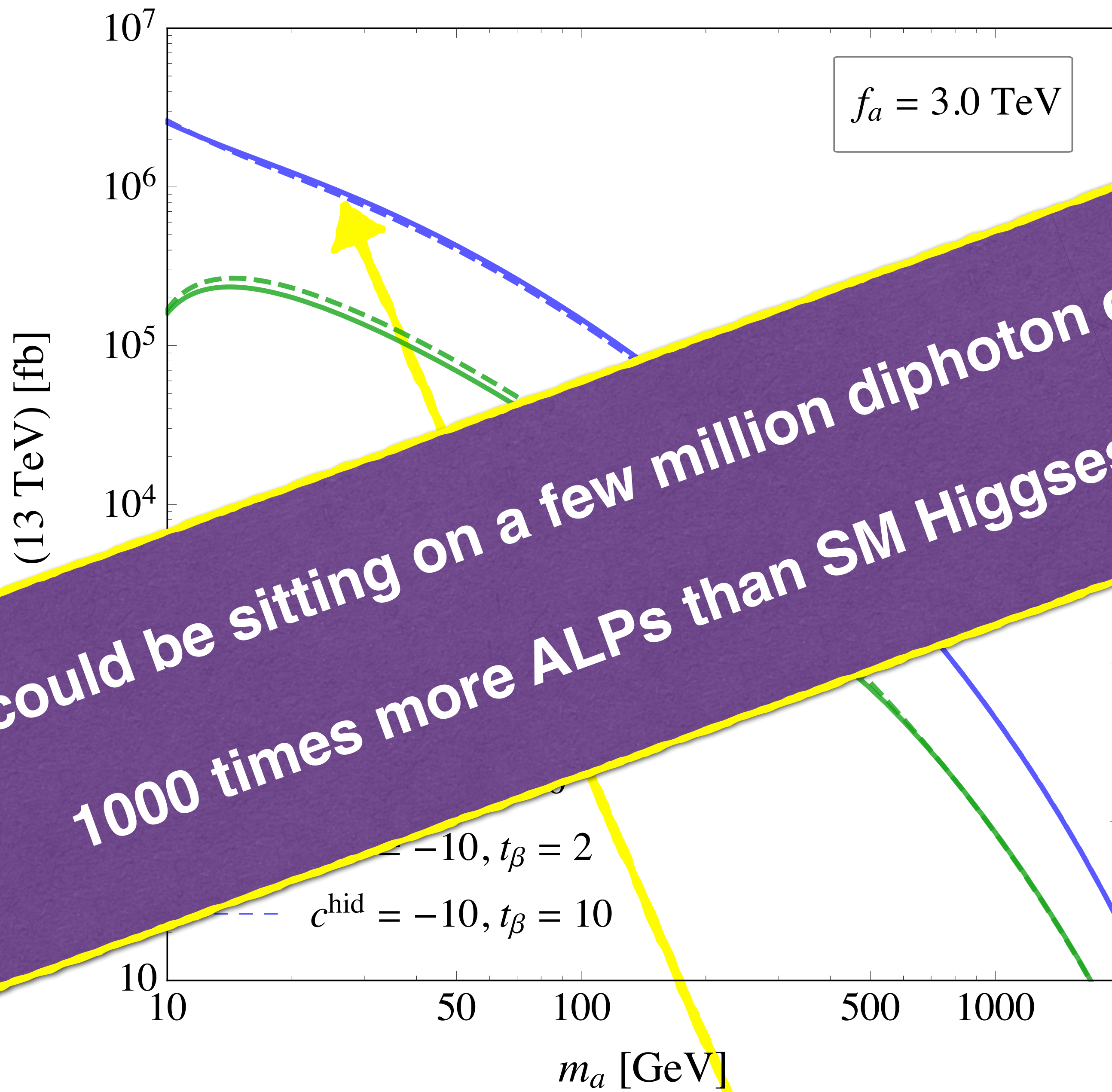




Production cross sections of ~ 10^5 pb are still allowed! $[f_a \approx 300\ \text{GeV}]$

ALP production at the LHC



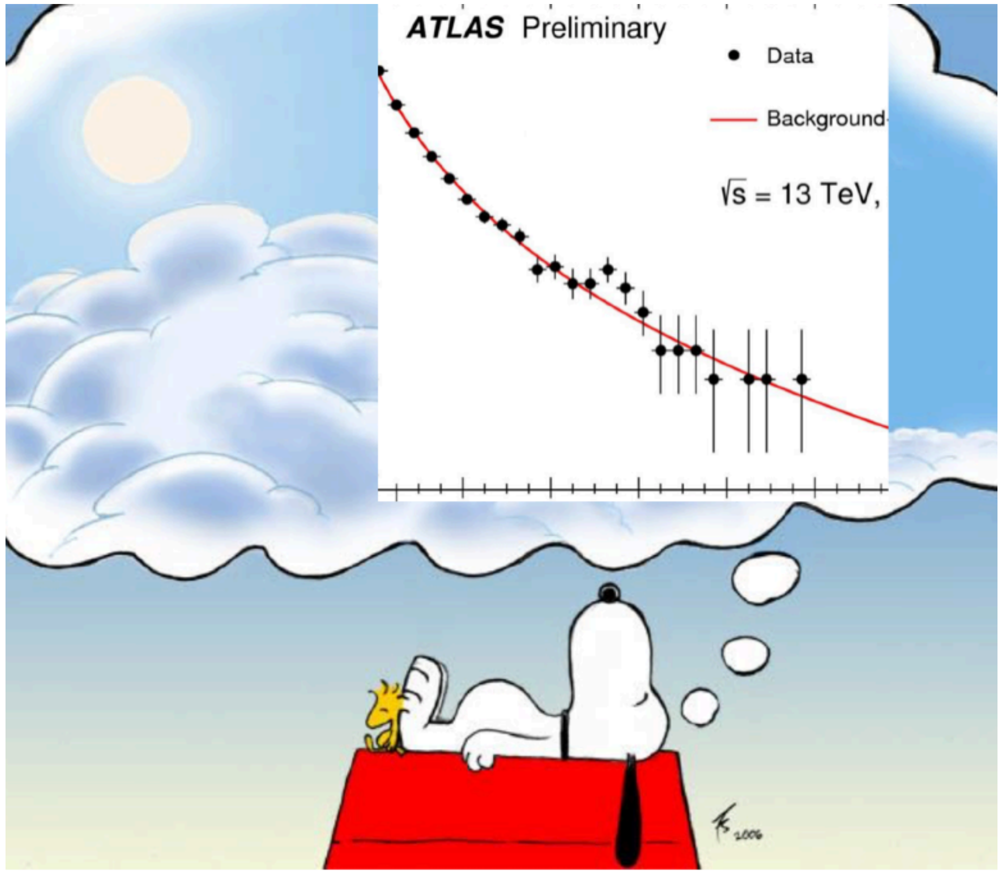


LHC could be sitting on a few million diphoton events!

1000 times more ALPs than SM Higgses!!

Production cross sections of ~ 10^5 pb are still allowed! $[f_a \approx 300$ GeV$]$

May our dreams come true?

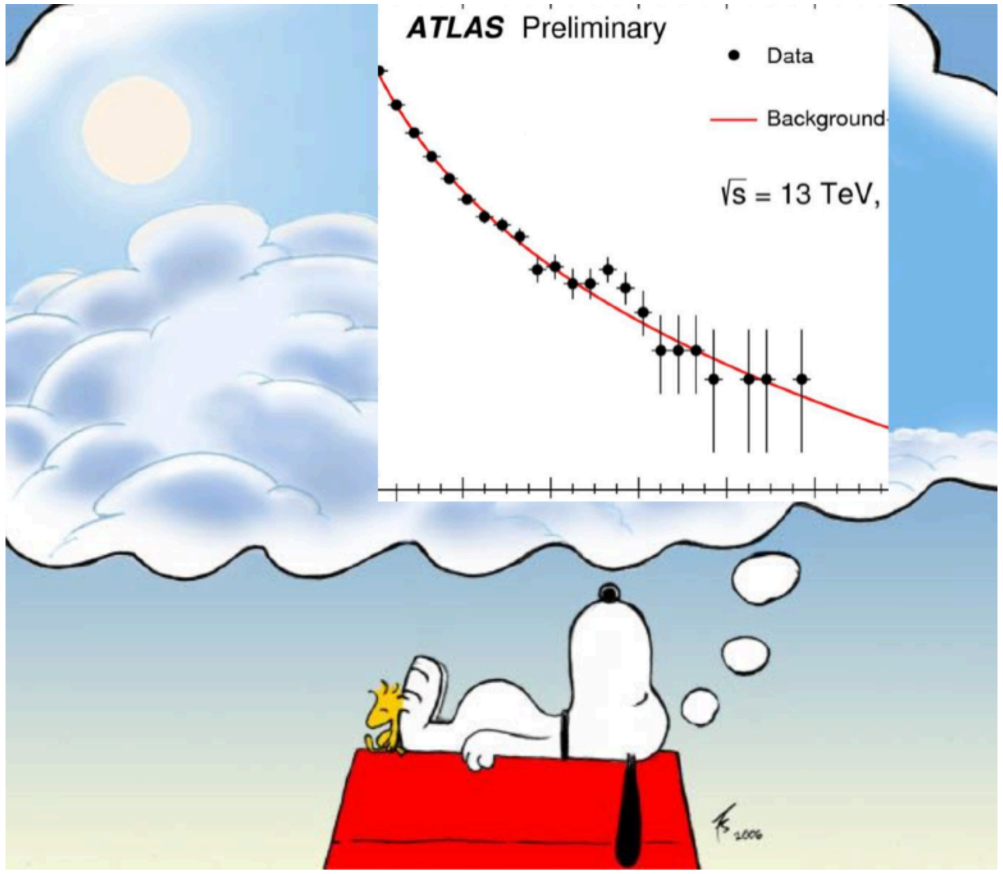


Why not $M_X < O(100)$ GeV ?

1. Theory bias towards high masses

2. "Low-mass already constrained by previous colliders (LEP,…)"

May our dreams come true?



Why not $M_X < O(100)$ GeV ?

3. “It is very difficult!” Minimal pT cuts, …

Why difficult to go below ~ 100 GeV?

$$M_{\gamma\gamma,jj,\ldots} > \Delta R \sqrt{p_{T_1}^{\min} p_{T_2}^{\min}}$$

Isolation of photon/jet/... $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$

Minimal cuts on transverse momenta

Two ways to lower $M_{\gamma\gamma}$

- Lower ΔR
- Lower $p_T^{\min}$

Lower $p_T^{\min}$?

$\Delta R \gtrsim 0.4$

D0 ($\sigma_{\gamma\gamma}$)	$p\bar{p} \to a \to \gamma\gamma$	4.2 fb^{-1}	1.96 TeV	$p_{T_1}, p_{T_2} > 21, 20$ GeV	[illegible]	[illegible]
CDF ($\sigma_{\gamma\gamma}$)	$p\bar{p} \to a \to \gamma\gamma$	5.36 fb^{-1}	1.96 TeV	$p_{T_1}, p_{T_2} > 17, 15$ GeV	[illegible]	[illegible]
ATLAS	$pp \to a \to \gamma\gamma$	4.9 fb^{-1}	7 TeV	$p_{T_1}, p_{T_2} > 25, 22$ GeV	[8]	9.4 GeV
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$m_{\gamma\gamma}^{\rm MIN}$

LHC pT cuts in diphoton cross section measurements

but LHC diphoton searches do not reach such low masses

Lower $p_T^{\min}$?

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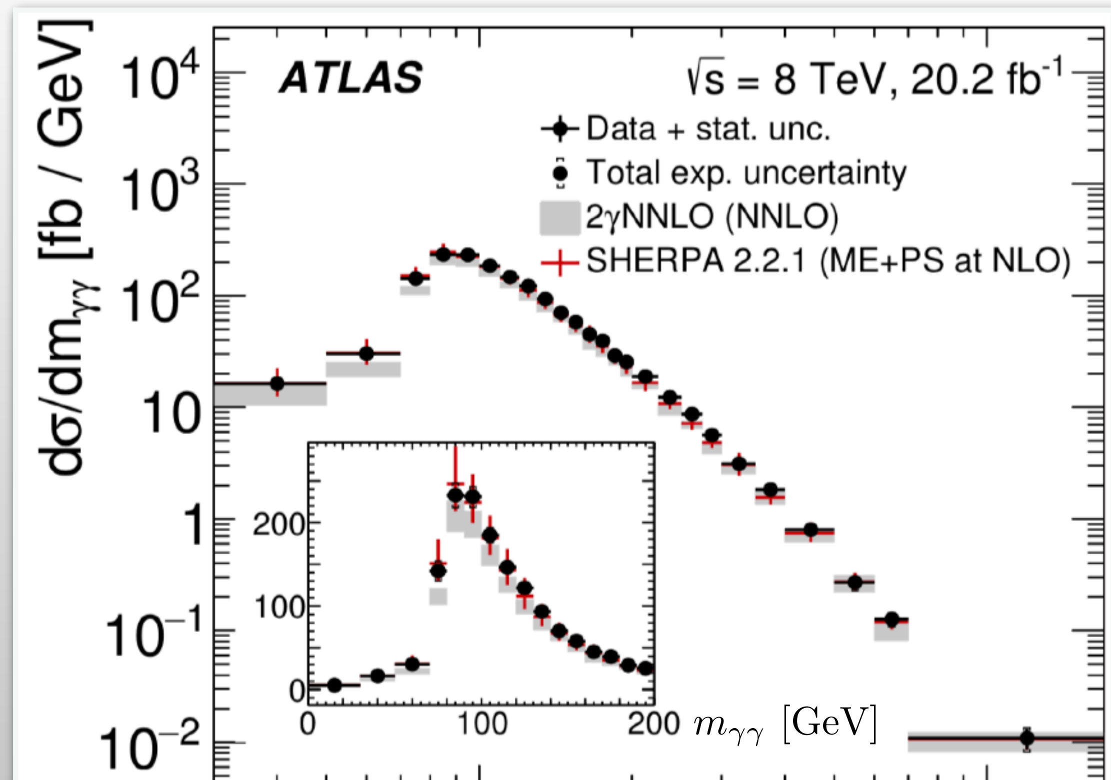
Why? **Background Shape**



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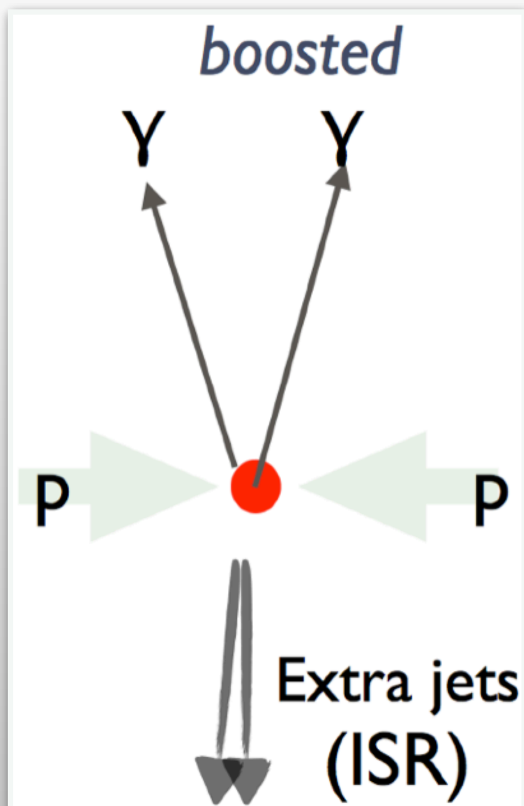

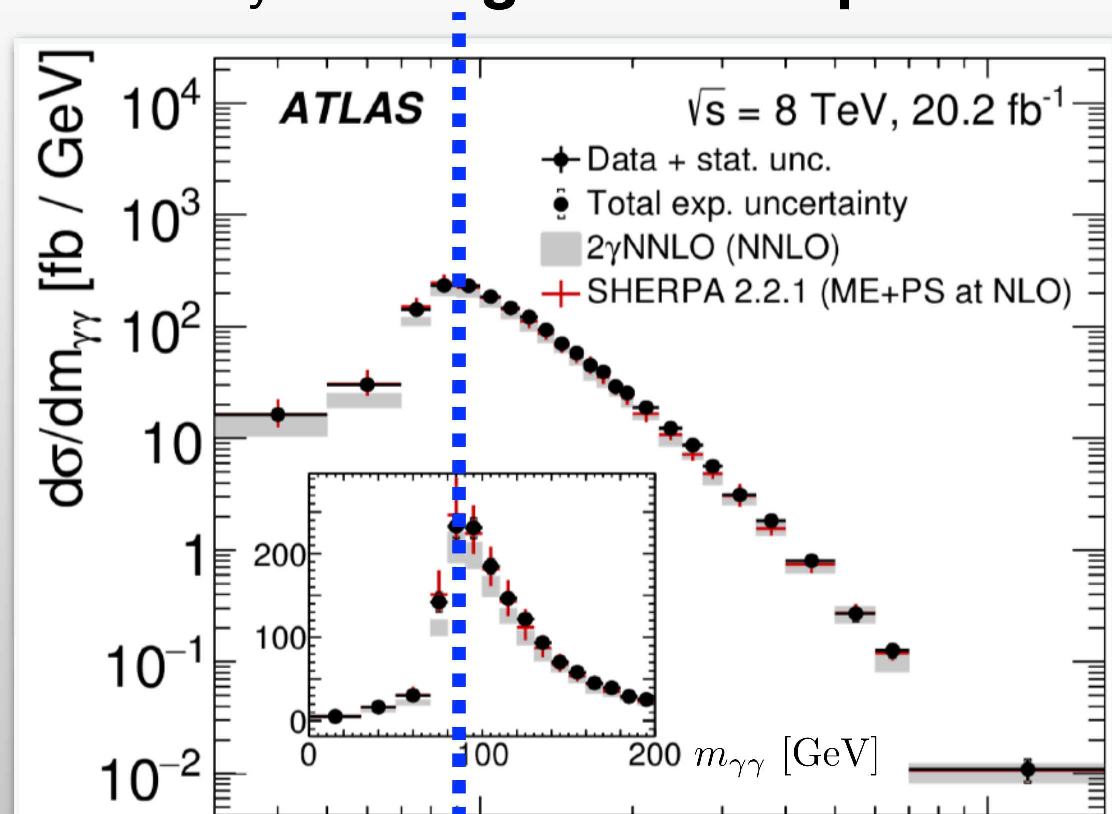

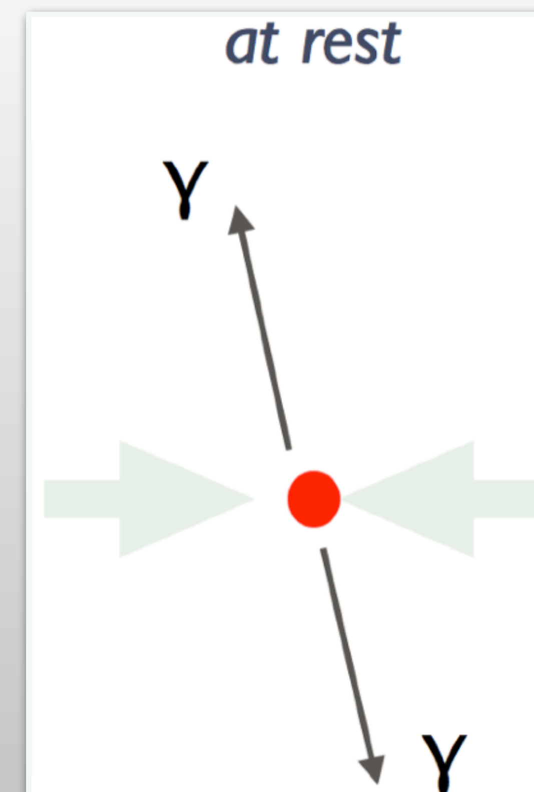

$$m_{\gamma\gamma} \simeq 2\, p_{T_1}^{\min}$$

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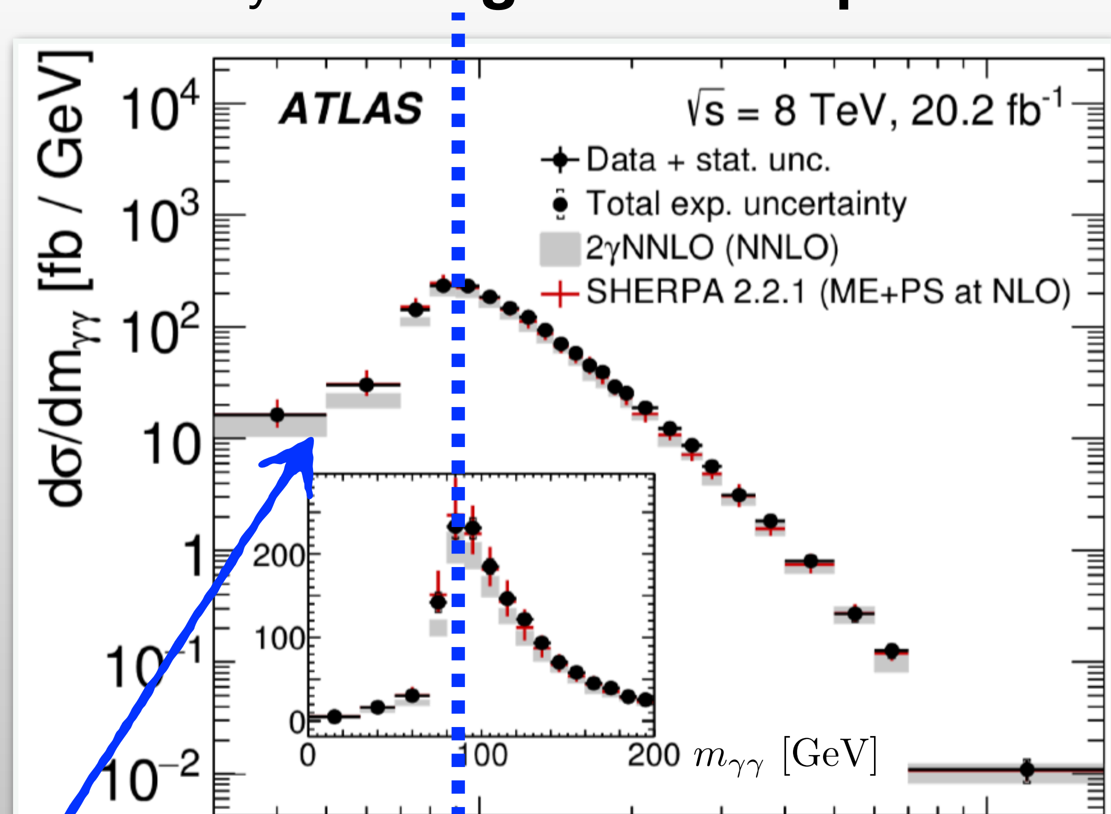
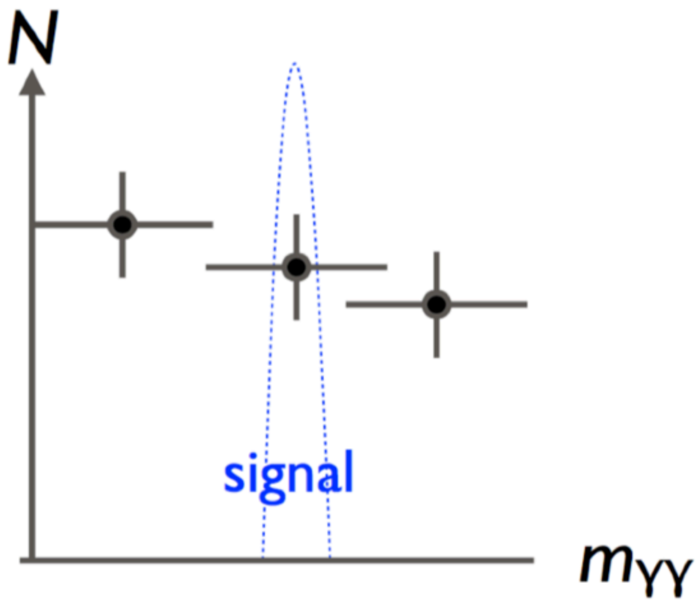


$$m_{\gamma\gamma} \simeq 2\, p_{T_1}^{\min}$$

Below pT cuts: Background has a structure, so **data-driven estimates are difficult**

New $\gamma\gamma$ Bound & Sensitivities

Starting point: inclusive **diphoton cross section measurements** @ ATLAS7,8 and CMS7



New Bound we assume zero knowledge of bkg

$$N_{\rm bin}^{\rm signal} < N_{\rm bin}^{\rm meas.}(1 + 2\,\Delta_{\rm bin})$$

experimental rel. uncertainty

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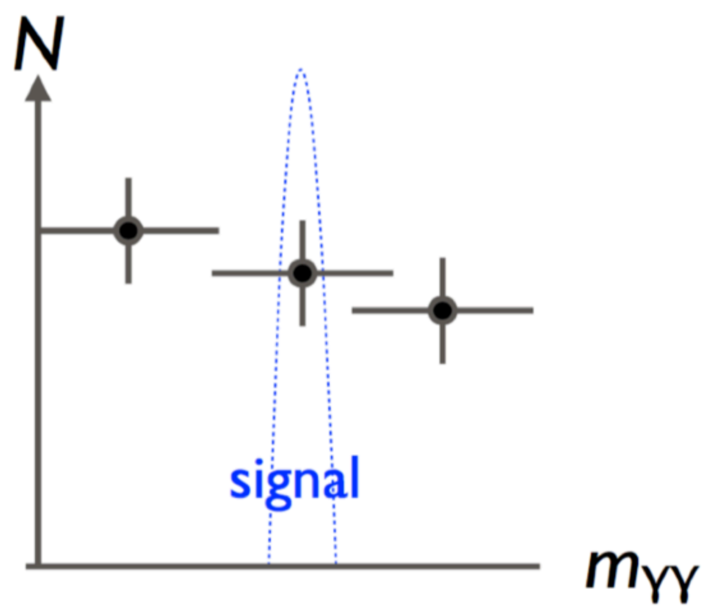

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experimental rel. uncertainty

Current LHC reach?

If bump-hunt on steep slope or if Monte Carlos improve:

$$N_{\rm bin}^{\rm signal} < N_{\rm bin}^{\rm meas.} \times 2\,\Delta_{\rm bin}$$

(we take data = SM prediction, and optimise binning)

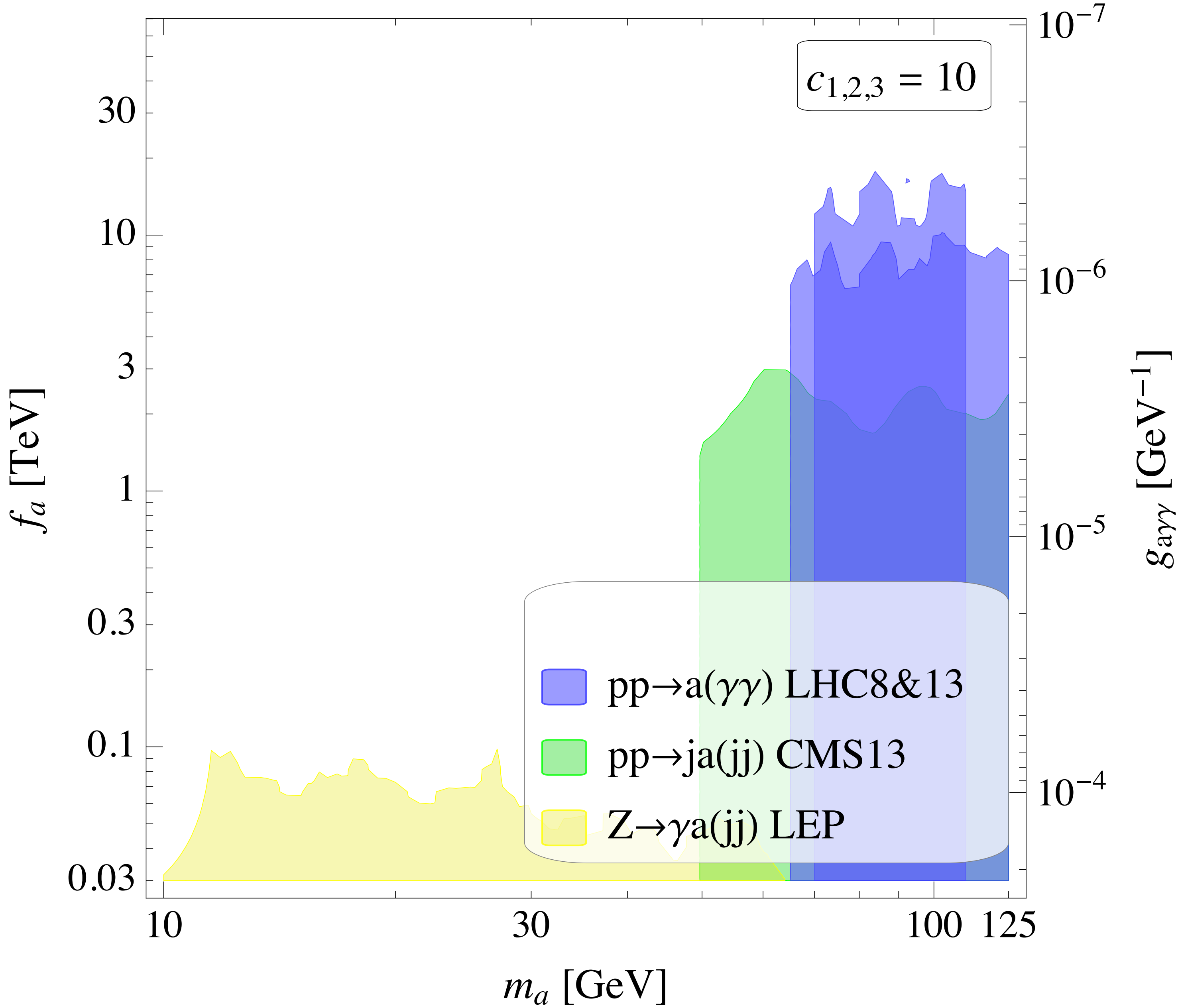
Future LHC Reach we rescale by simulation of bkg with <u>same cuts</u> at <u>different energies</u>

[Madgraph+Pythia+Delphes]

Impact on ALP parameter space

$$\mathcal{L}_{\rm int} = \frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$$

$$\alpha_1 = \frac{5}{3}\alpha_y$$



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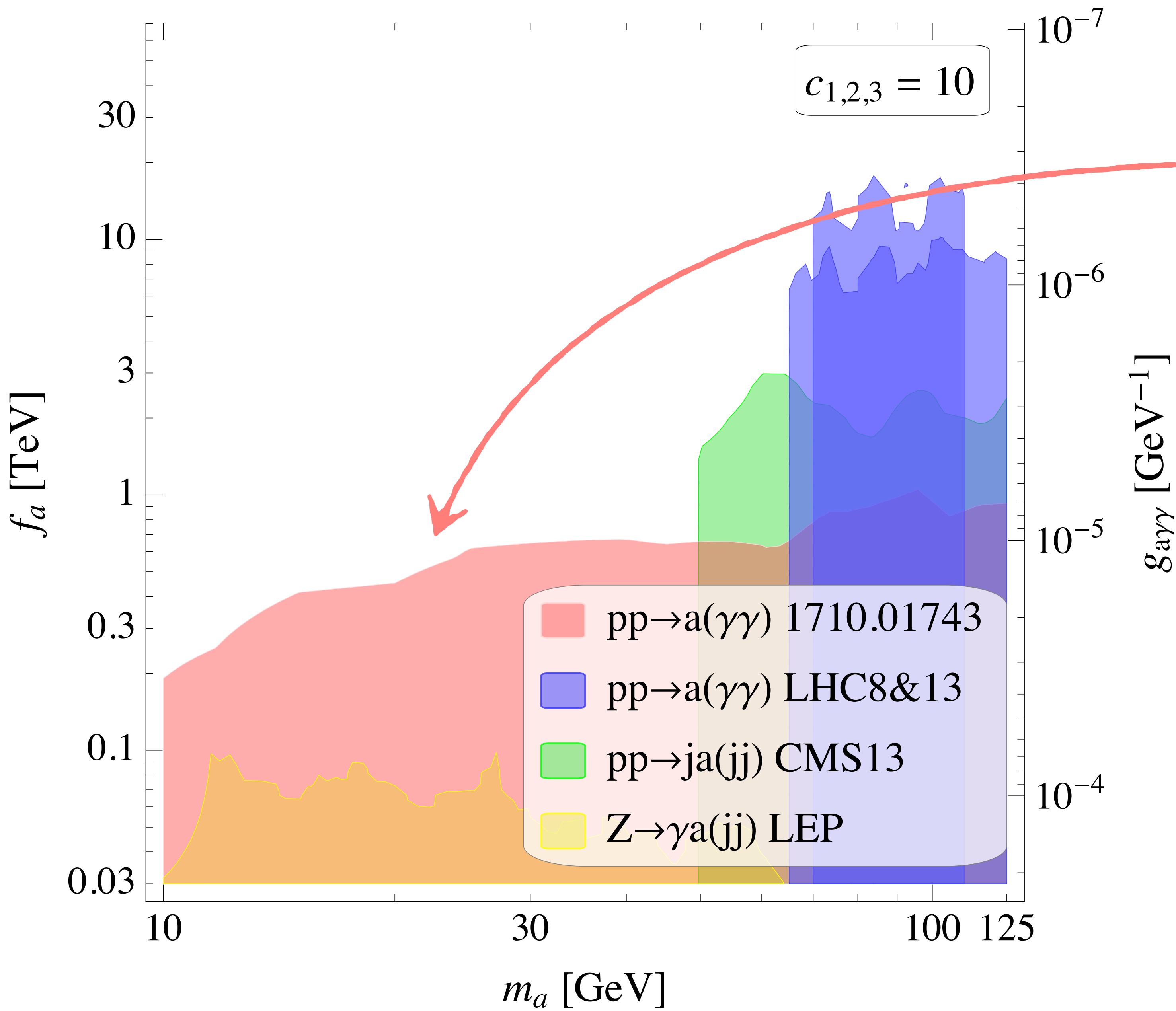

Our simple **bound** is (by far) the strongest one!

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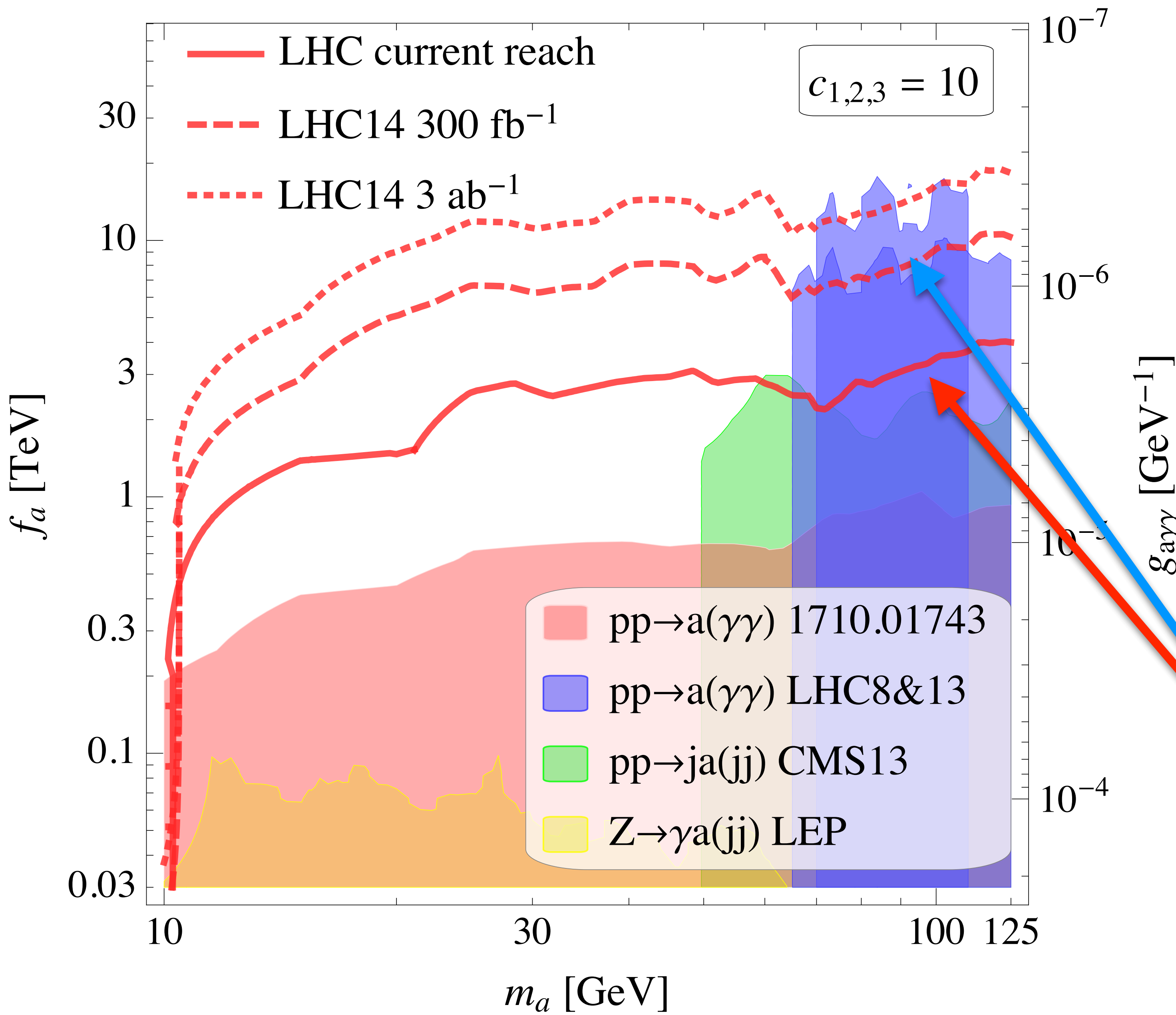

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Memo:
reach assumes bump hunt on steep slope or improvement in SM prediction

But at least we have been conservative for masses that LHC already explored

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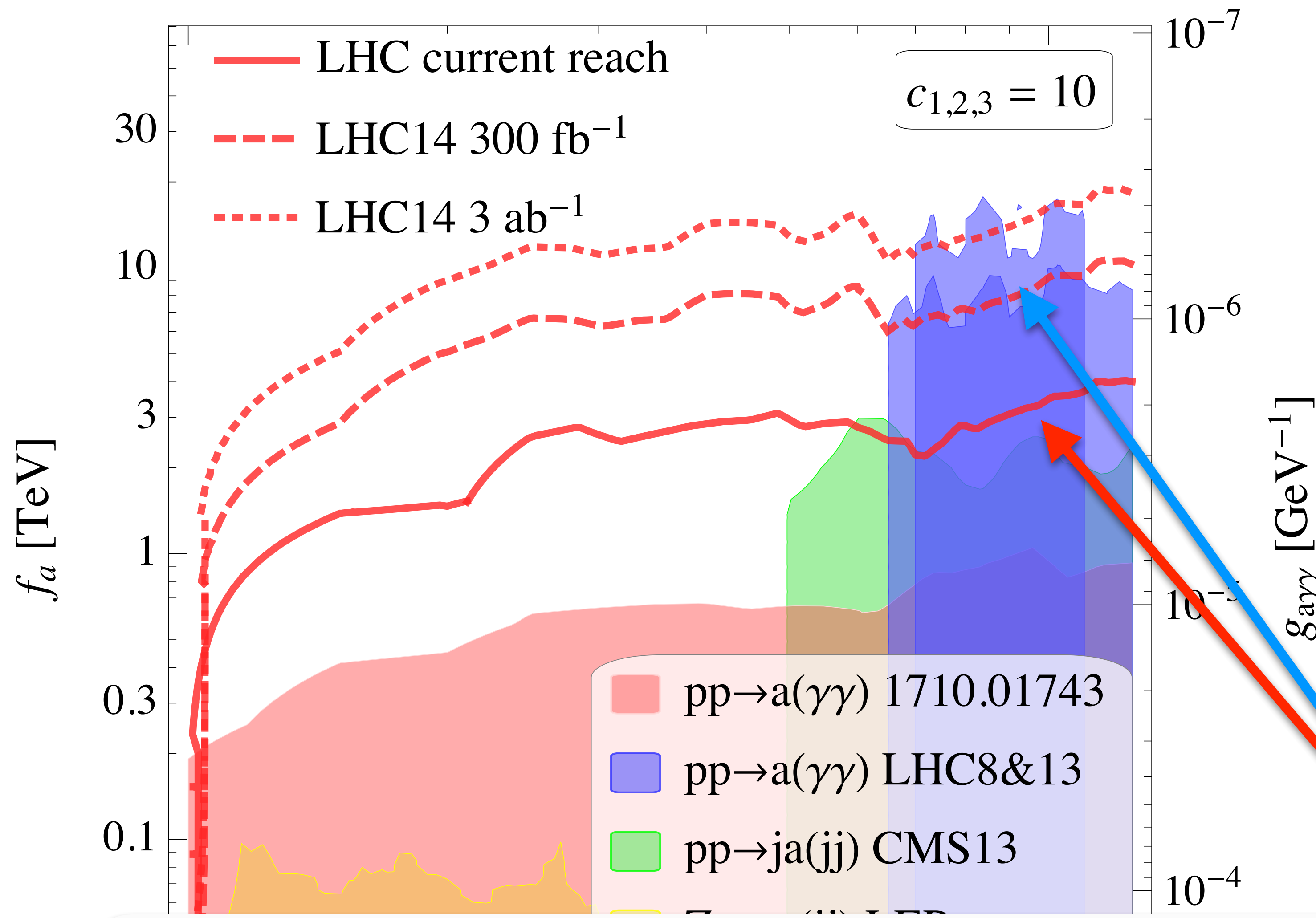

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But at least we have been conservative ... ady explored

Could be useful to **non-ALP scenarios**!

Light Z' (e.g. as DM mediators)

Extra Higgses Delgado+ 1603.00962

....

So, what should ATLAS & CMS do?

Study so far shows clearly an unexplored potential, but

Challenge: need improvement in Monte Carlo to predict the backgrounds

or being able to hunt bumps on steep data

$$M_{\gamma\gamma,jj,\ldots} > \Delta R \sqrt{p_{T_1}^{\min} p_{T_2}^{\min}}$$

- Lower ΔR

  and look for resonances recoiling against a jet (or any ISR)

  Background is smooth and one does not need Monte Carlos!

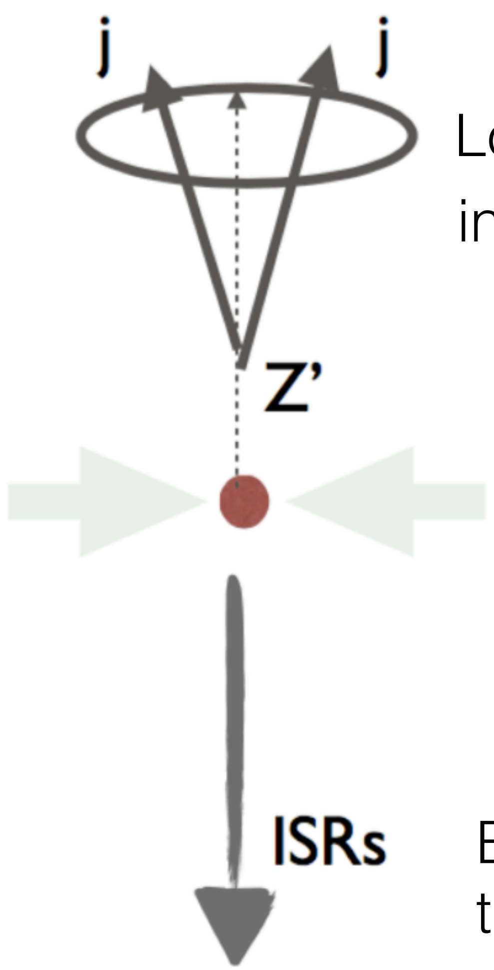
Lower ΔR: The Present

				m_{jj}^{MIN}	
CMS	$pp \to a \to jj$	18.8 fb^{-1}	8 TeV	500 GeV	[38]
ATLAS	$pp \to a \to jj$	20.3 fb^{-1}	8 TeV	350 GeV	[39]
CMS	$pp \to a \to jj$	12.9 fb^{-1}	13 TeV	600 GeV	[40]
ATLAS	$pp \to a \to jj$	3.4 fb^{-1}	13 TeV	450 GeV	[41]
CMS	$pp \to ja \to jjj$	35.9 fb^{-1}	13 TeV	50 GeV	[42]

Done recently in dijet, tremendous improvement in mass reach!

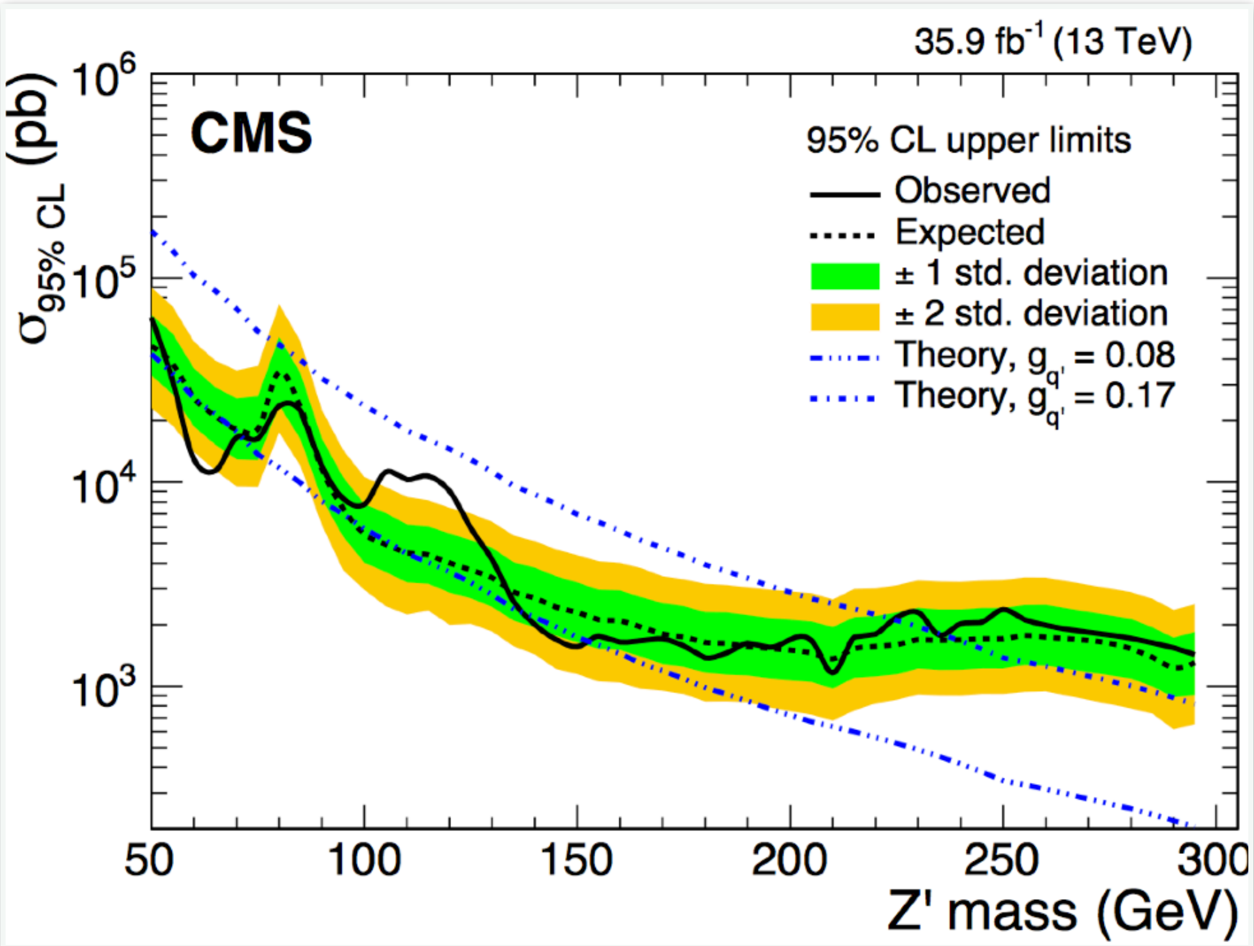
CMS 1710.00159

ATLAS 1801.08769



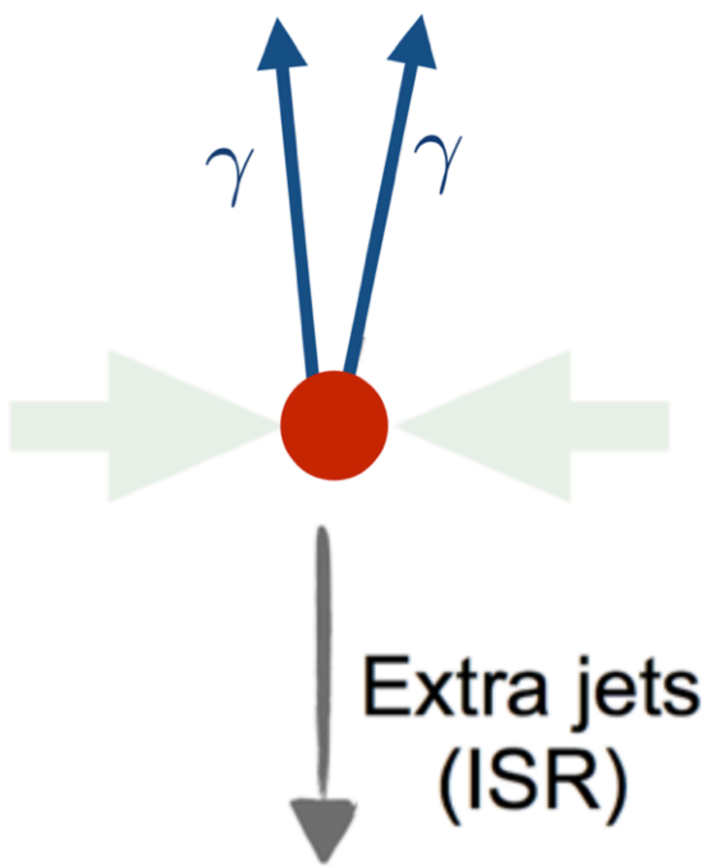
Look for **boosted** resonance in jet substructure

Extra hard object to pass the trigger



Lower ΔR: The Future

Low Mariotti Redigolo FS Tobioka in progress



They managed with jets, why not with photons?

Diphotons boosted vs a hard jet $p_T^a > 500 \text{ GeV}$

Photons get collimated $\Delta R \simeq \frac{2m_a}{p_T^a}$

Standard isolation rejects signal

$$\sum_{i \neq \gamma_{\text{test}}}^{\Delta R < R_{\text{iso}}} p_{T,i} < \# \qquad \sum_{i \neq \gamma_{\text{test}}}^{\Delta R < R_{\text{iso}}} p_{T,i} \Big/ E_{T,\gamma_{\text{test}}} < \#$$

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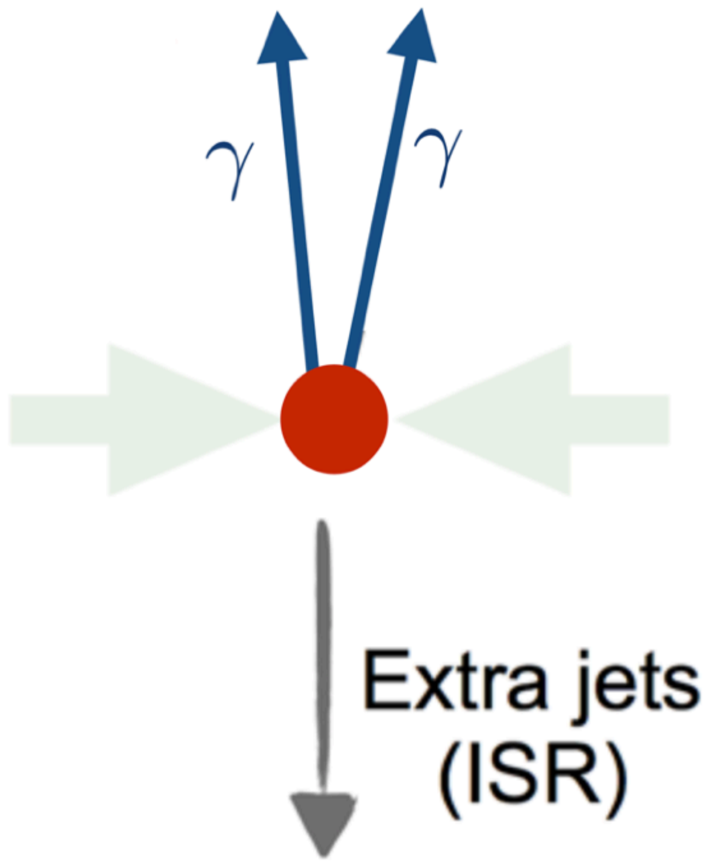

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Modify isolation! <u>(NB: simpler than photon-jet substructures…)</u>

It works!

$$\sum_{i \neq \gamma_{\text{test}}, \gamma_1}^{\Delta R < R_{\text{iso}}} p_{T,i} \qquad \sum_{i \neq \gamma_{\text{test}}, \gamma_1}^{\Delta R < R_{\text{iso}}} p_{T,i} \Big/ E_{T,\gamma_{\text{test}}}$$

final checks and optimisations in progress

Lower ΔR: The Future

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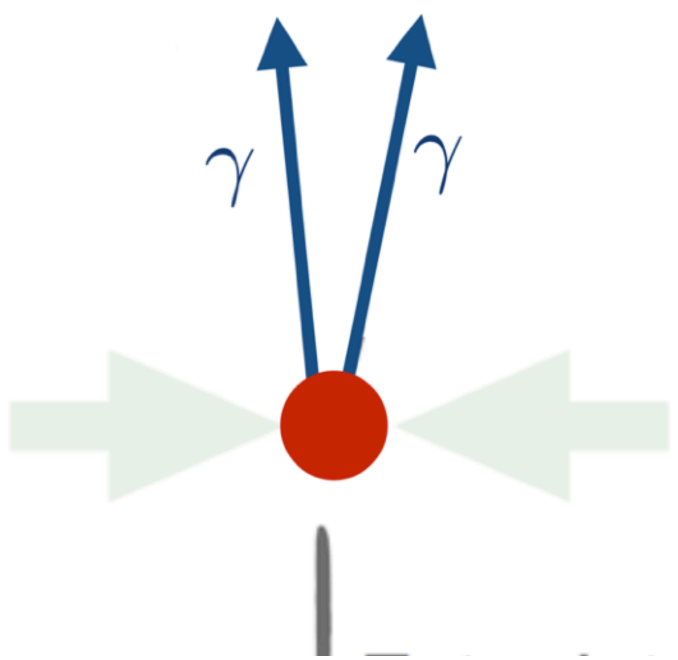

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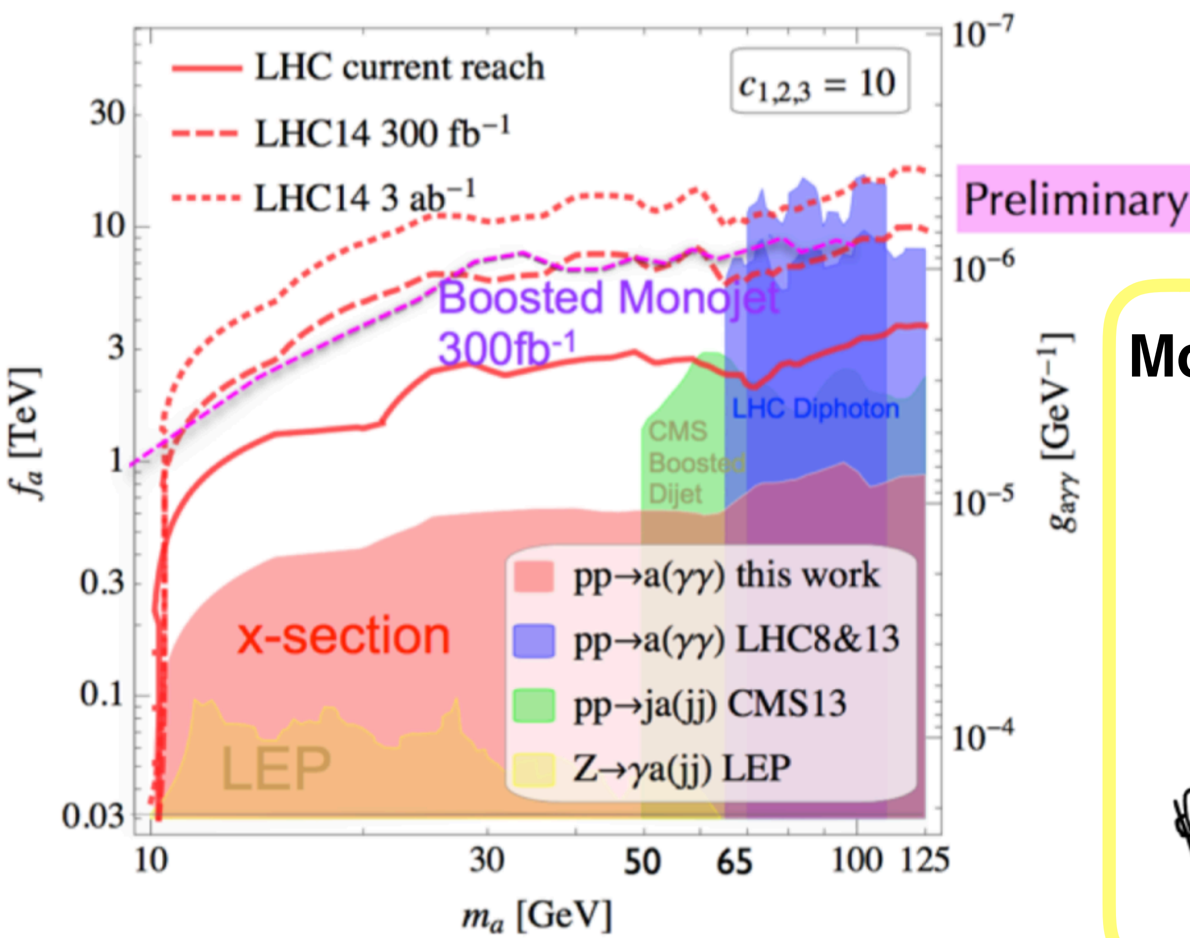

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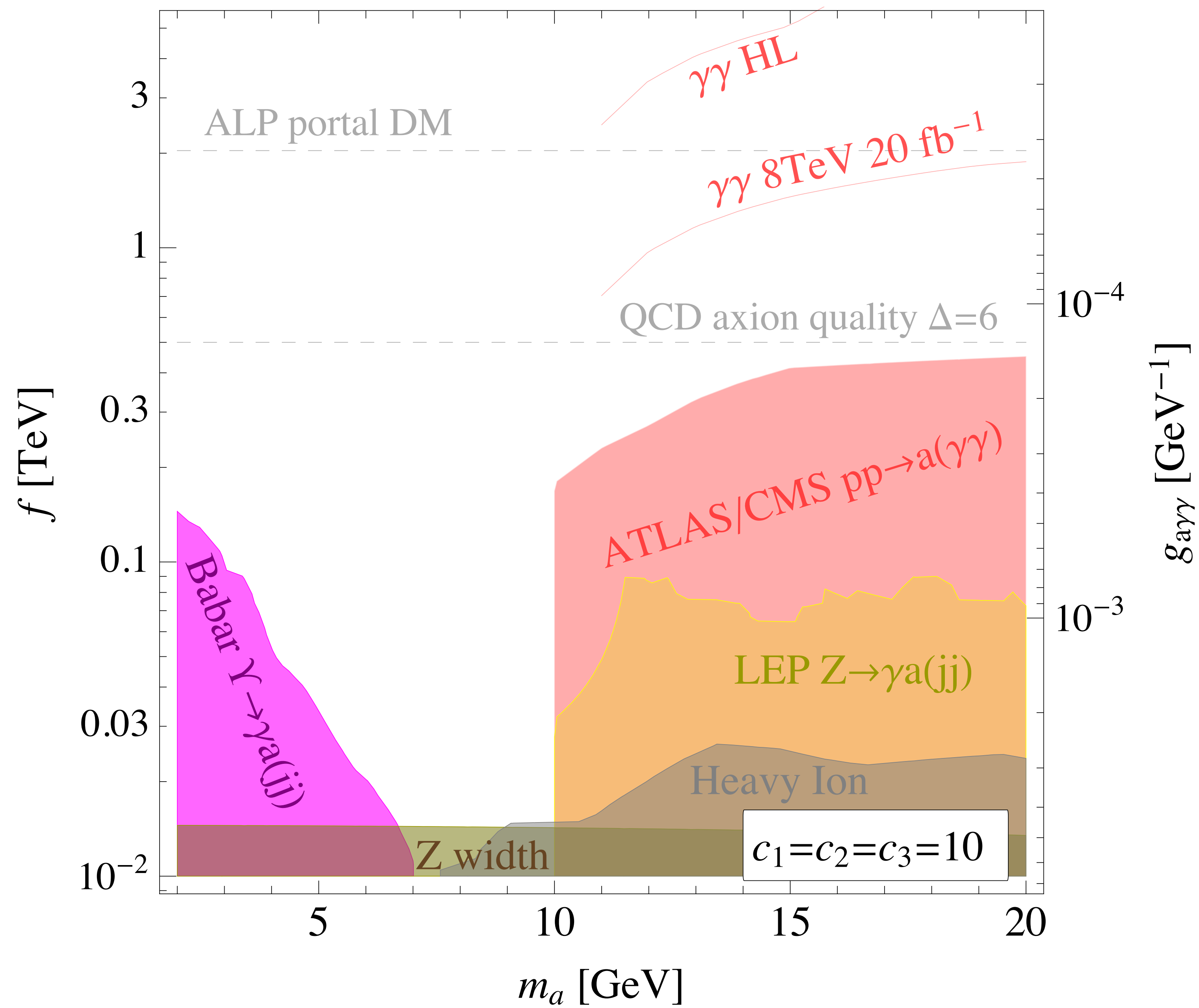
final checks and optimisations in progress

Even smaller masses?



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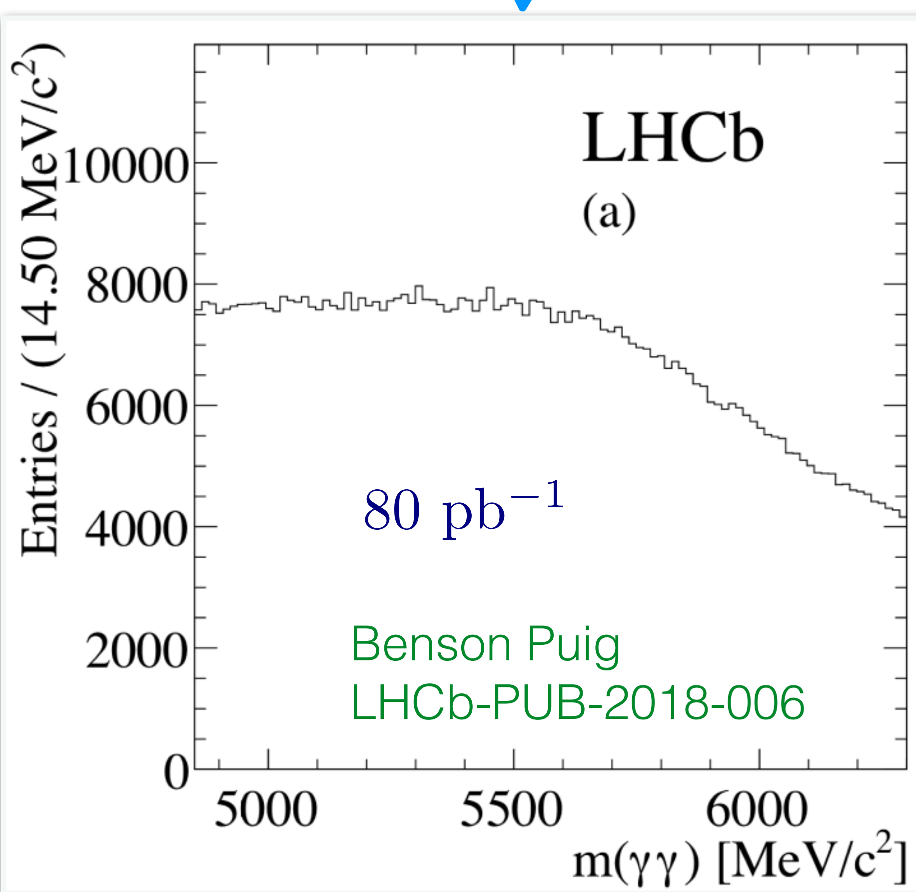
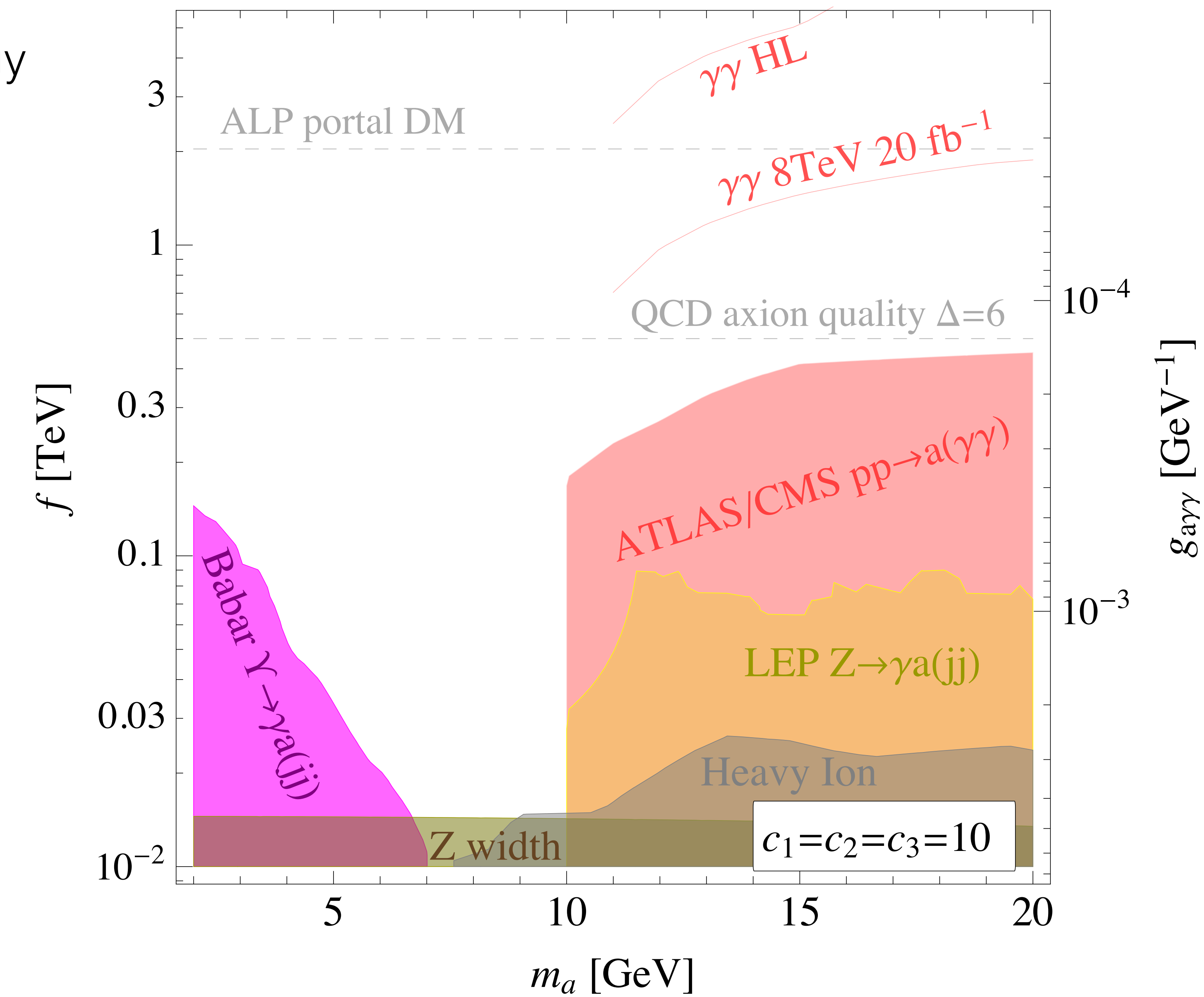
Even smaller masses? LHCb

LHCb aims at competitive search for $B_s \to \gamma\gamma$

They published note with search strategy



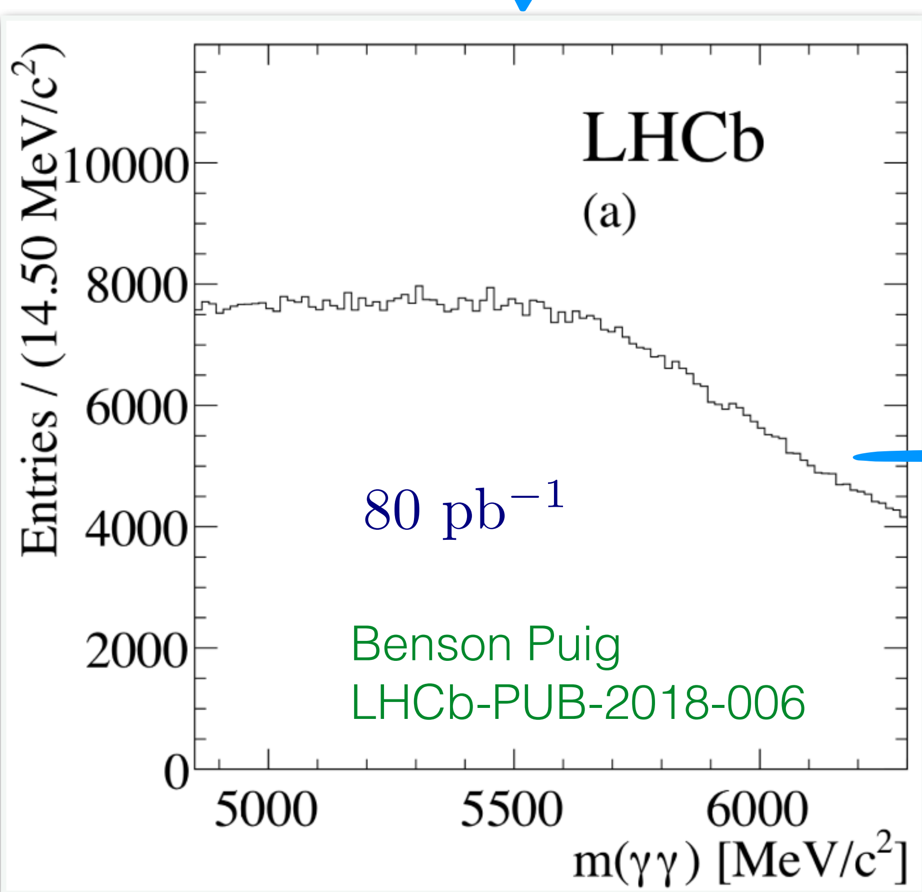


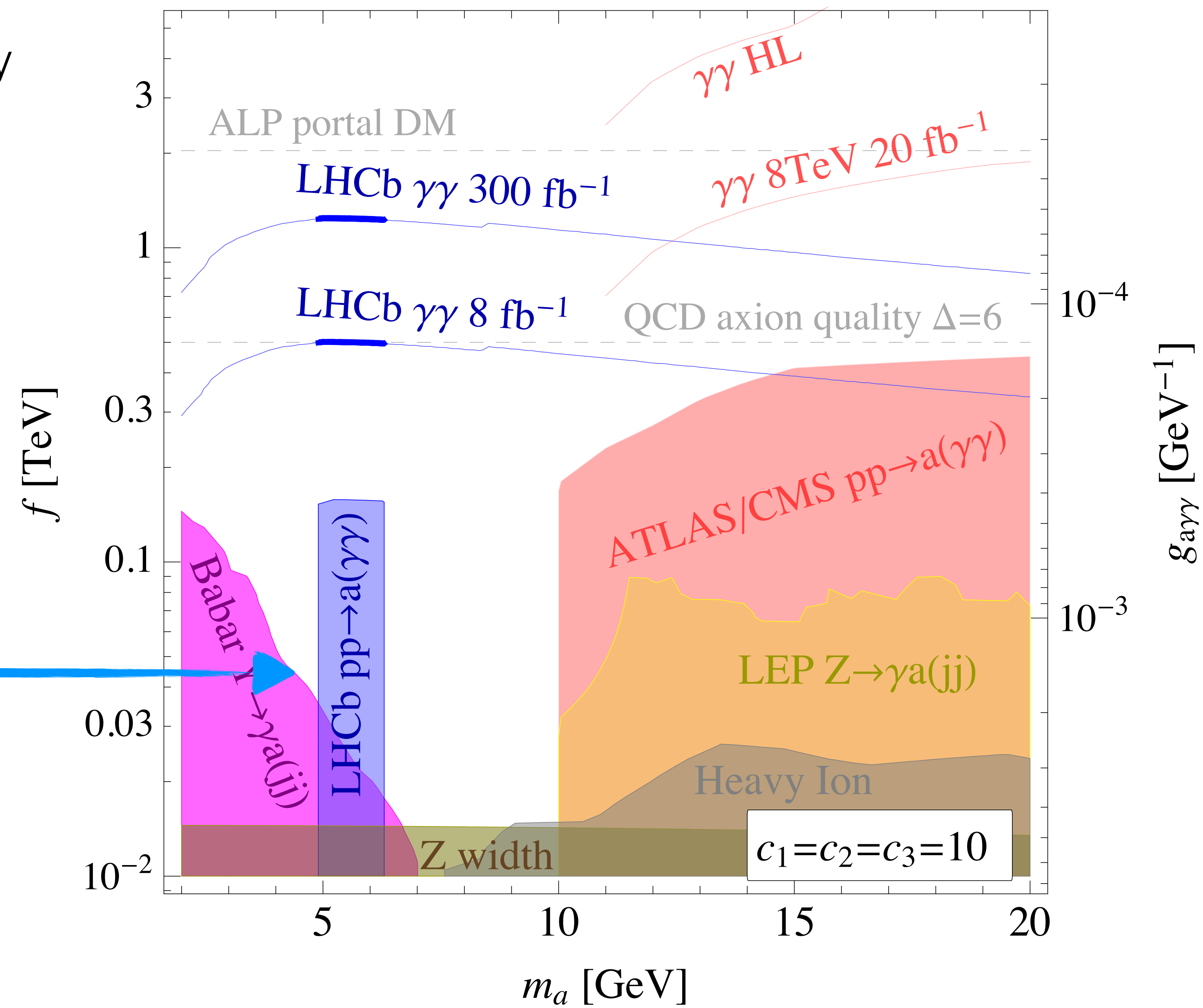
$$\mathcal{L}_{\rm int} = \frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$$

Even smaller masses? LHCb

LHCb aims at competitive search for $B_s \to \gamma\gamma$

They published note with search strategy





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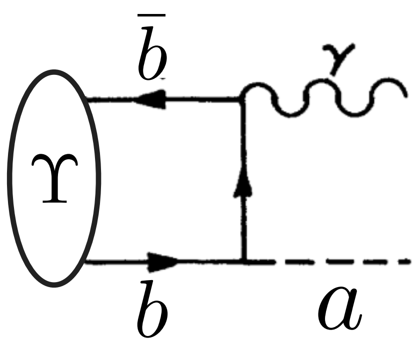
Even smaller masses? Belle-II



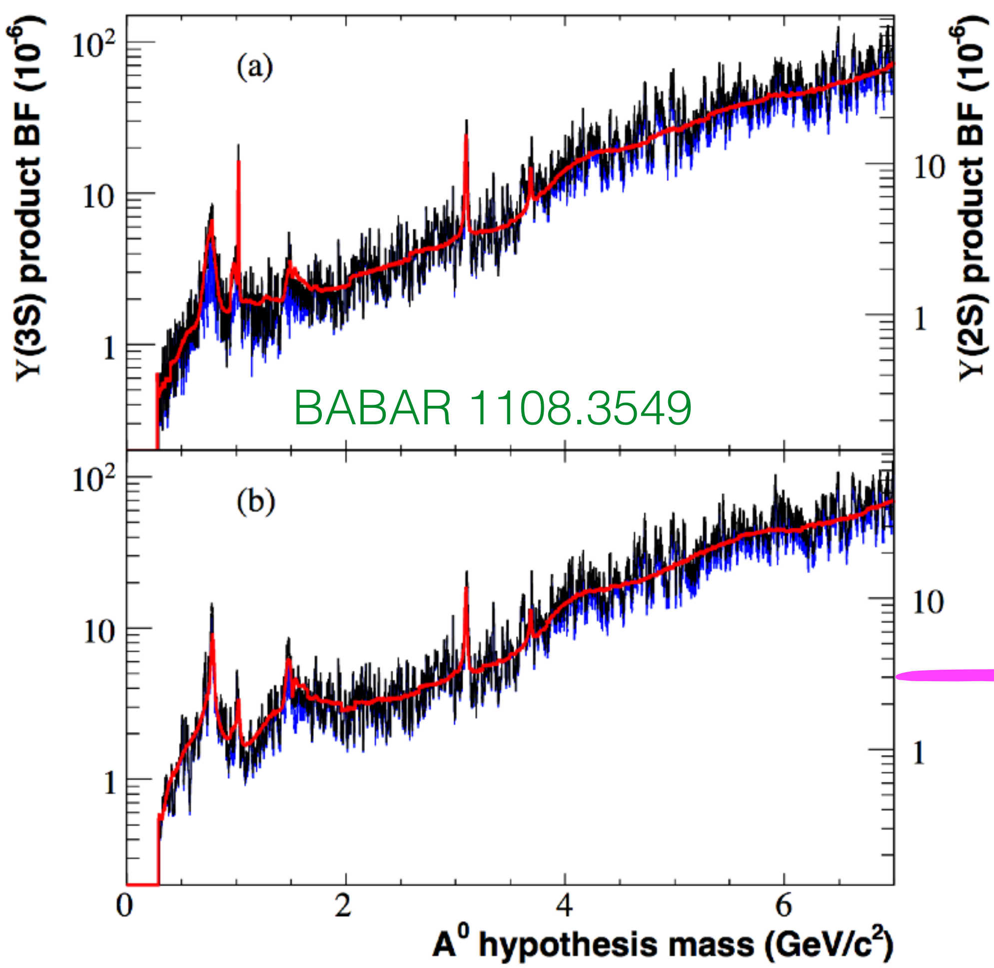
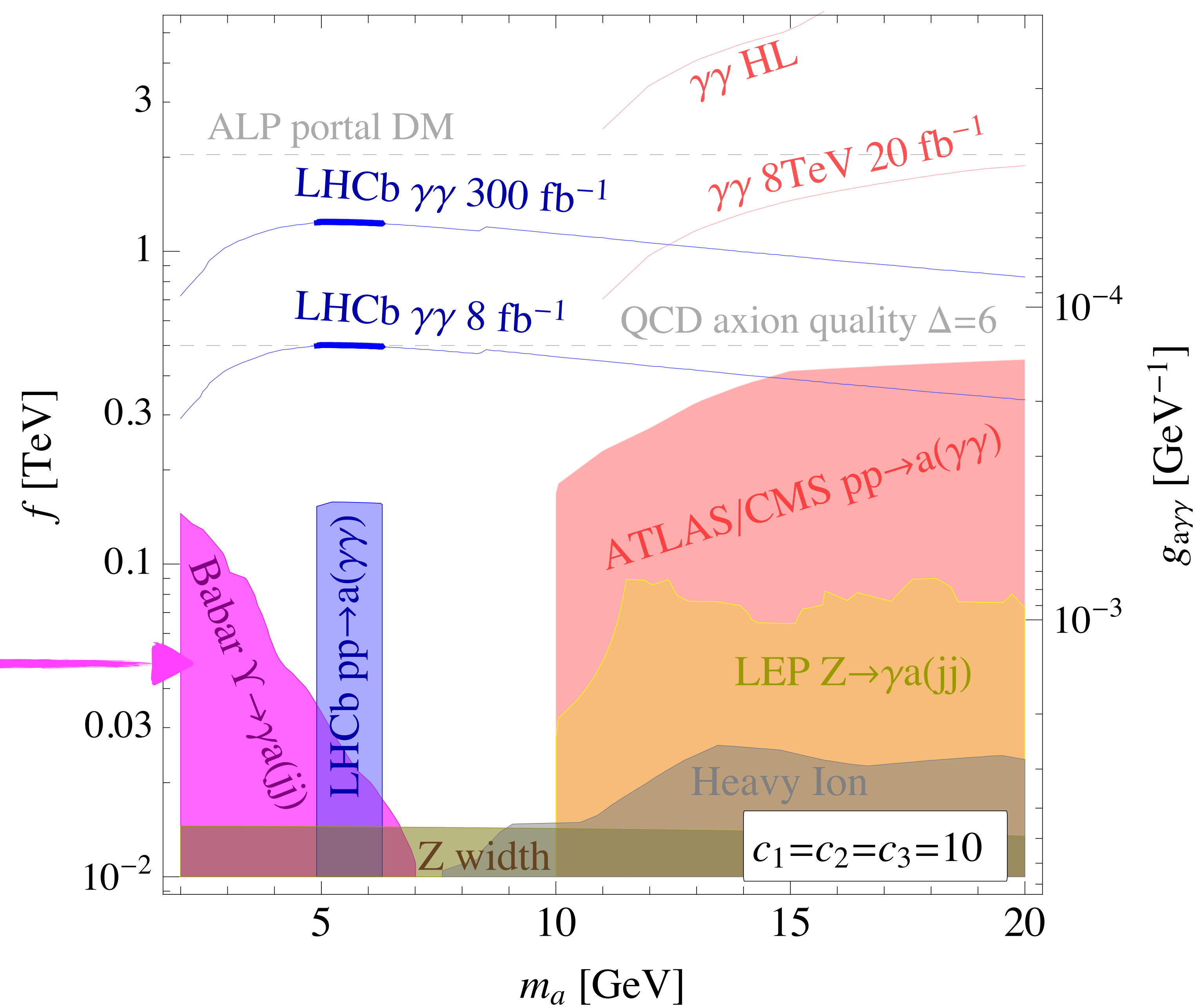


FIG. 5: 90% CL upper limits on product branching fractions (BF) (left axis) $\mathcal{B}(\Upsilon(3S) \to \gamma A^0) \cdot \mathcal{B}(A^0 \to \text{hadrons})$ and (right axis) $\mathcal{B}(\Upsilon(2S) \to \gamma A^0) \cdot \mathcal{B}(A^0 \to \text{hadrons})$, for (a) CP-all analysis, and (b) CP-odd analysis. The overlaid curves in red are the limits expected from simulated experiments, while the blue curves are the limits from statistical errors only. The



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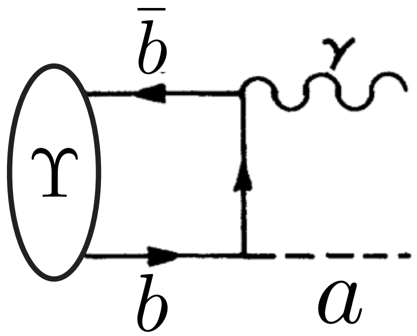
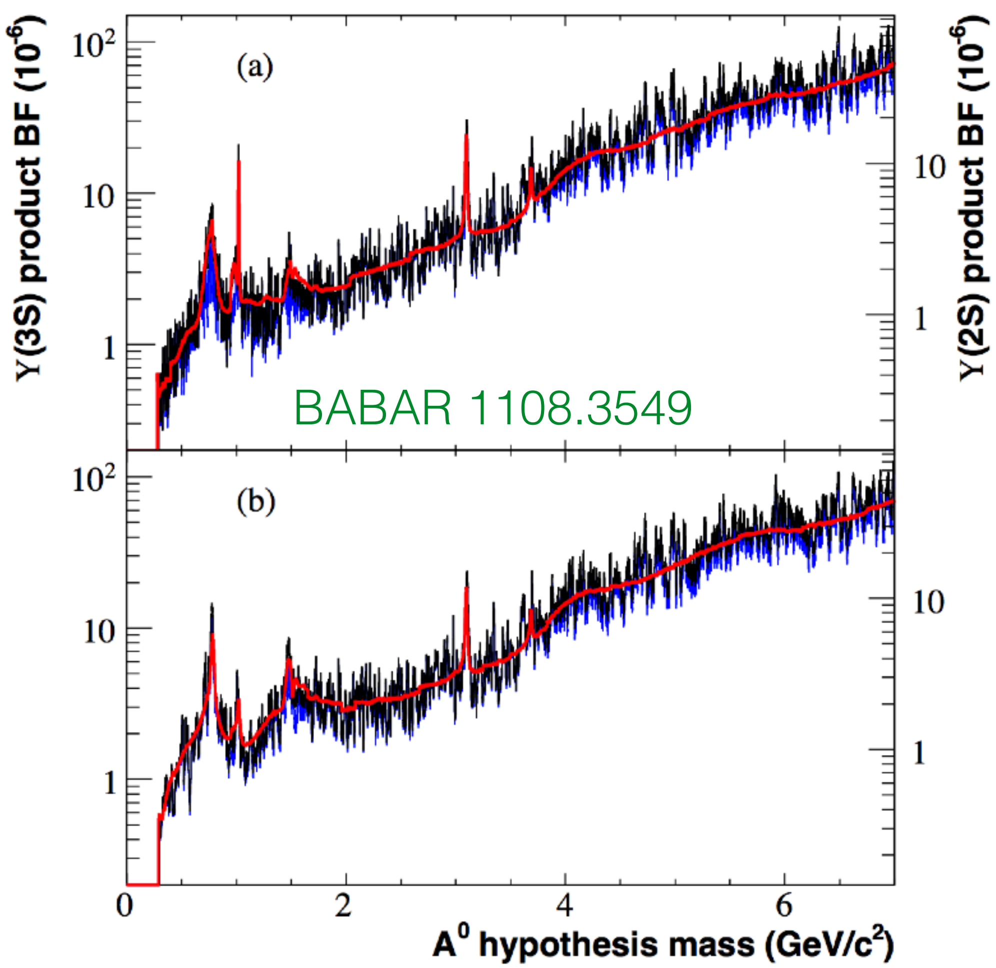
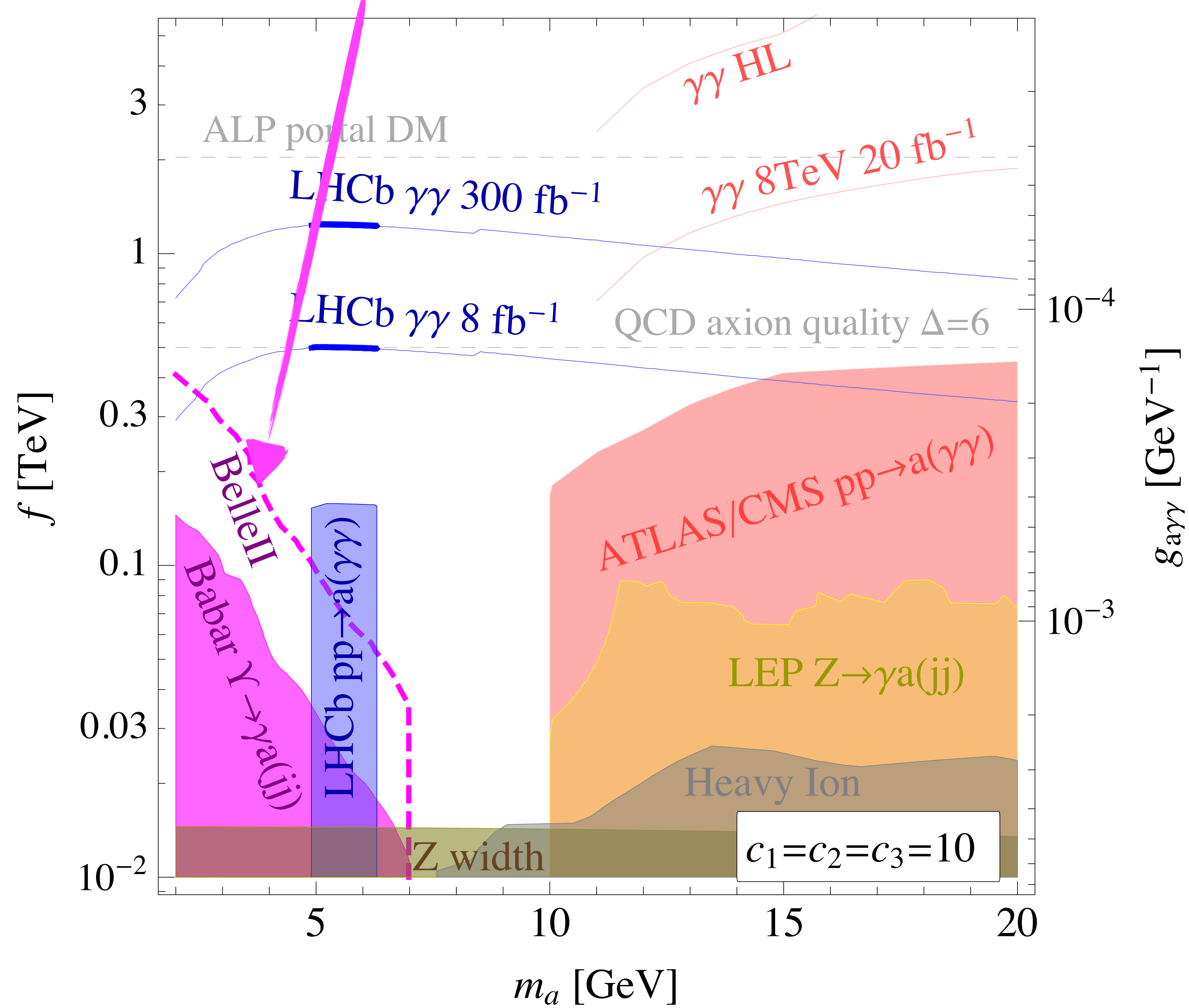
Even smaller masses? Belle-II



Assumes Belle-II produces **100x** more $\Upsilon(3S)$ than BABAR ($\Upsilon(1S,2S)$ good as well)





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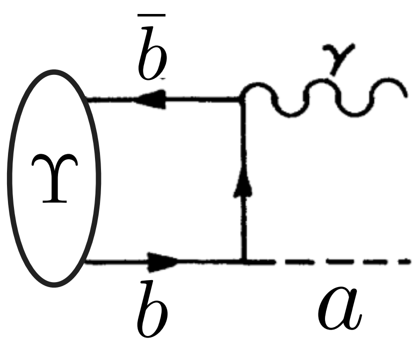
$$\mathcal{L}_{\text{int}} = \frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$$

Cid-Vidal Mariotti Redigolo FS Tobioka 1810.xxxxx

Even smaller masses? Belle-II



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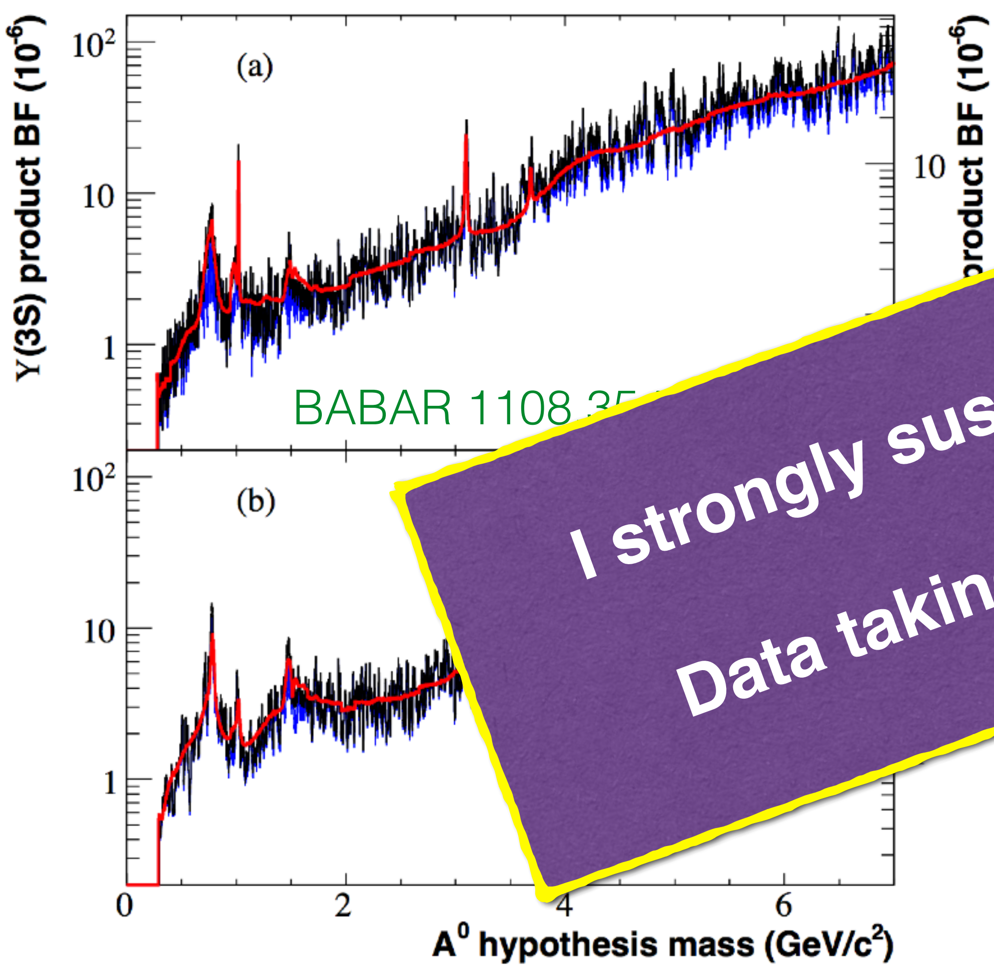

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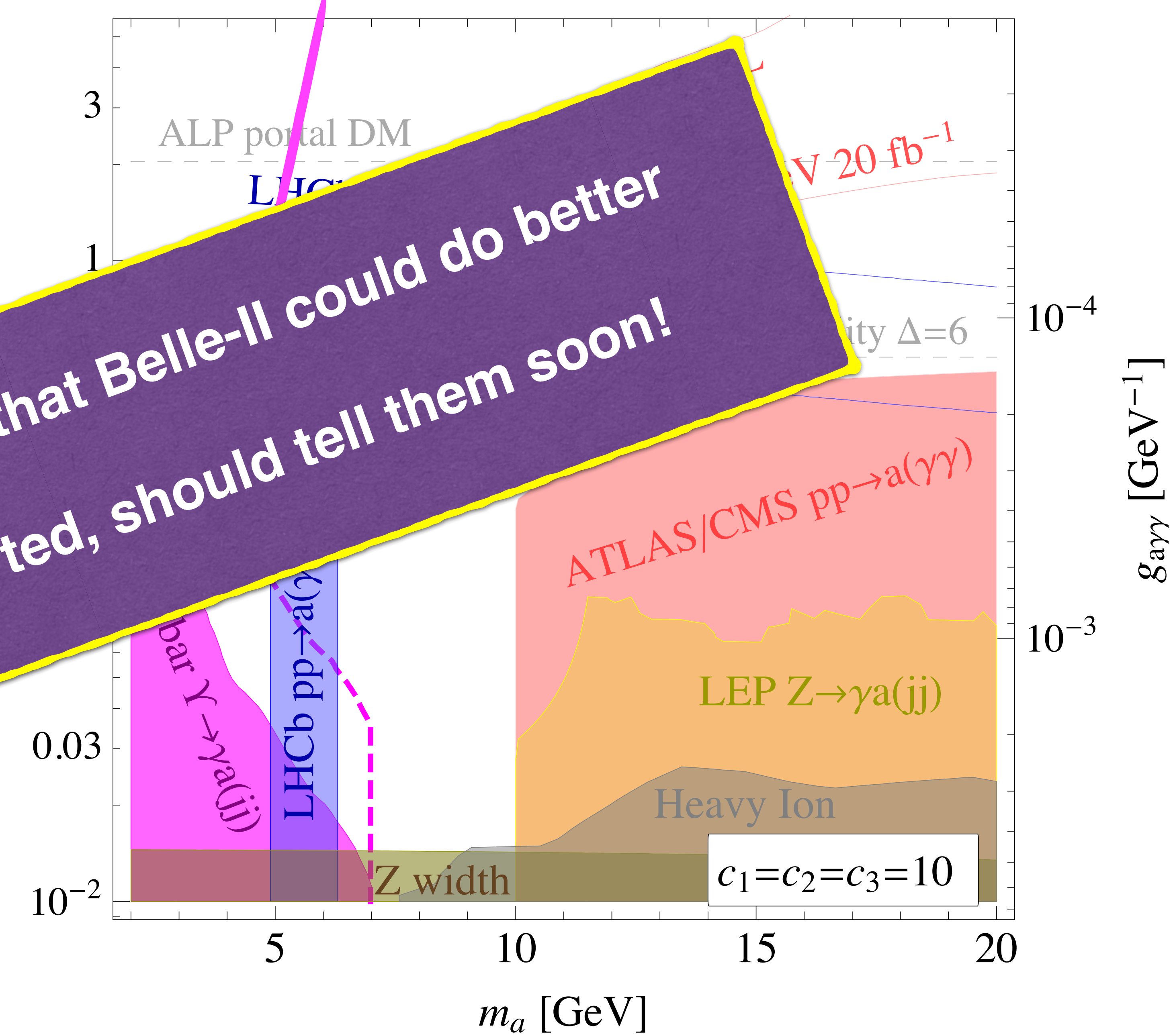


I strongly suspect that Belle-II could do better

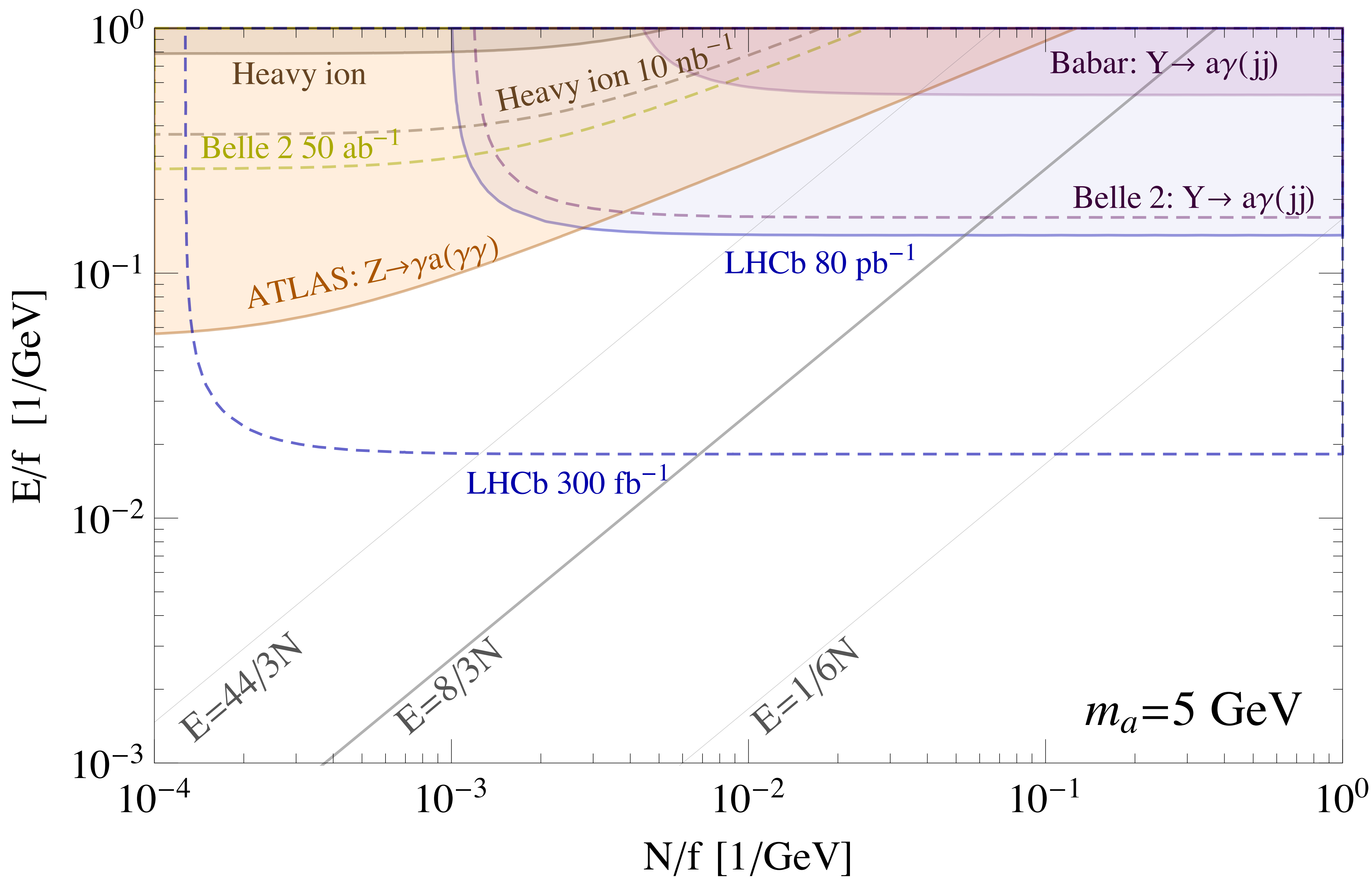
Data taking started, should tell them soon!

$$\mathcal{L}_{\rm int} = \frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$$

What if different couplings?

$$\mathcal{L}_{\text{eff}} \supset \frac{N\alpha_3}{4\pi}\frac{a}{f}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{E\alpha_{\text{em}}}{4\pi}\frac{a}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Cid-Vidal Mariotti Redigolo FS Tobioka 1810.xxxxx



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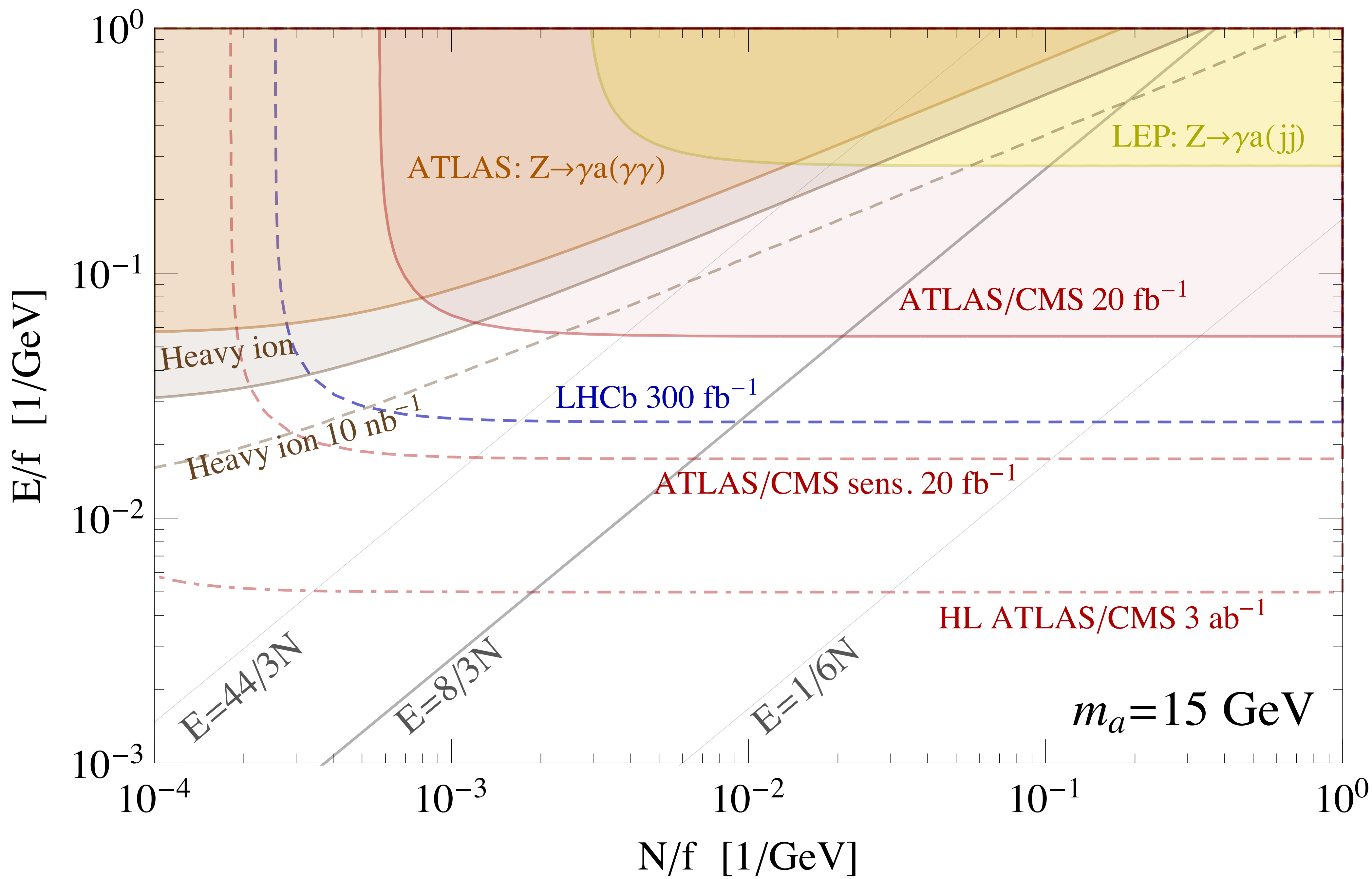
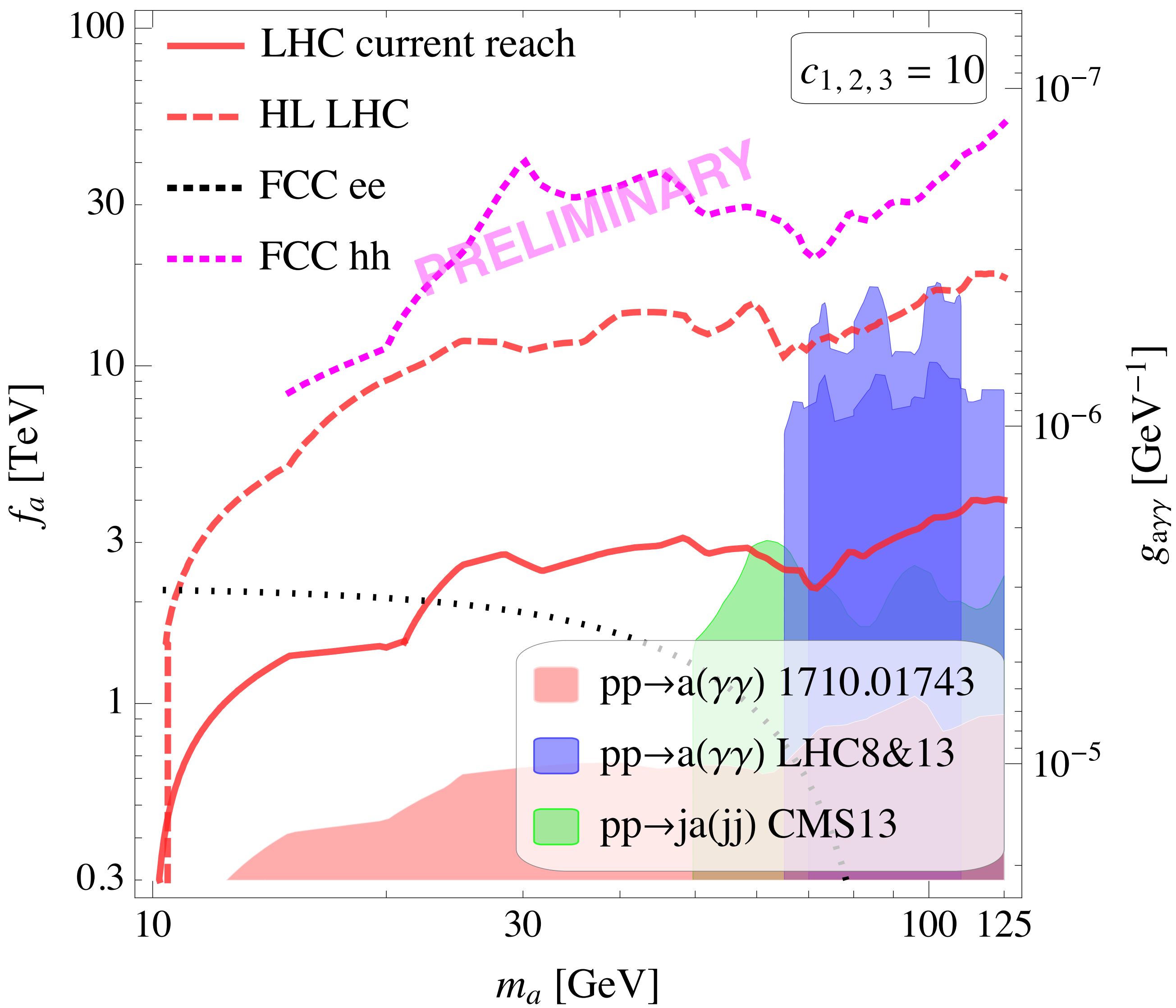
Cid-Vidal Mariotti Redigolo FS Tobioka 1810.xxxxx



Even more future?

FCC ee reach computed rescaling
LEP limits on $\mathrm{BR}[Z \to \gamma a(jj)]$
and assuming 10^{12} Z bosons

If $aG\tilde{G}$ switched on
HL-LHC wins over FCC ee



Even more future?

FCC ee reach computed rescaling
LEP limits on $\mathrm{BR}[Z \to \gamma a(jj)]$
and assuming 10^{12} Z bosons

If $aG\tilde{G}$ switched on
HL-LHC wins over FCC ee

FCC hh reach computed like LHC14 one
[4., from simulations, Lumi= $3\ \mathrm{ab}^{-1}$]

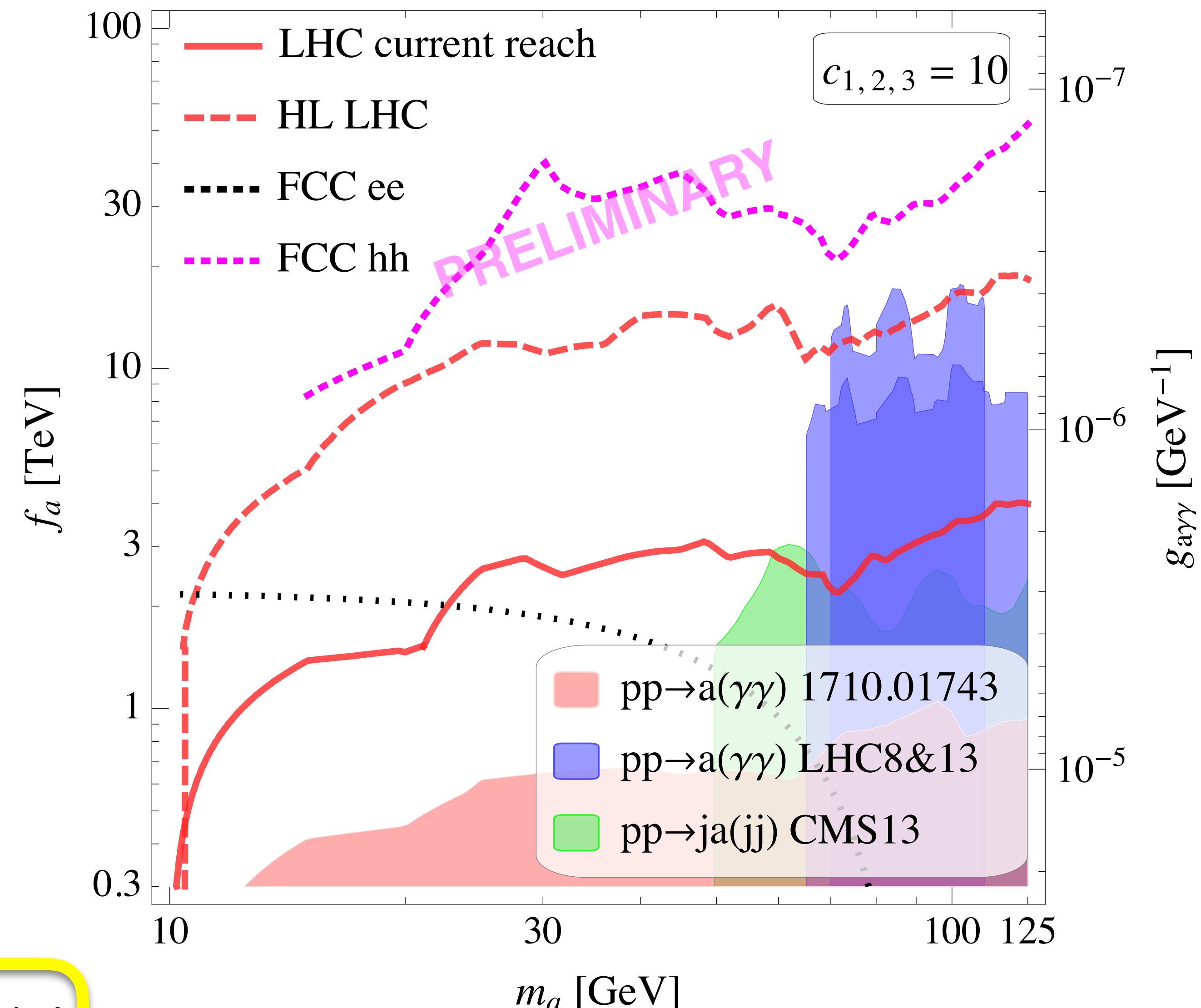
NB. pT cuts as in ATLAS8 (30, 40 GeV)

Still, speculative even for FCC standards!

this search has not even been performed at 8 TeV

at 100 TeV game could be very different (larger boosts,…)

Thoughts in progress…



New BSM searches at LHC & Belle-II

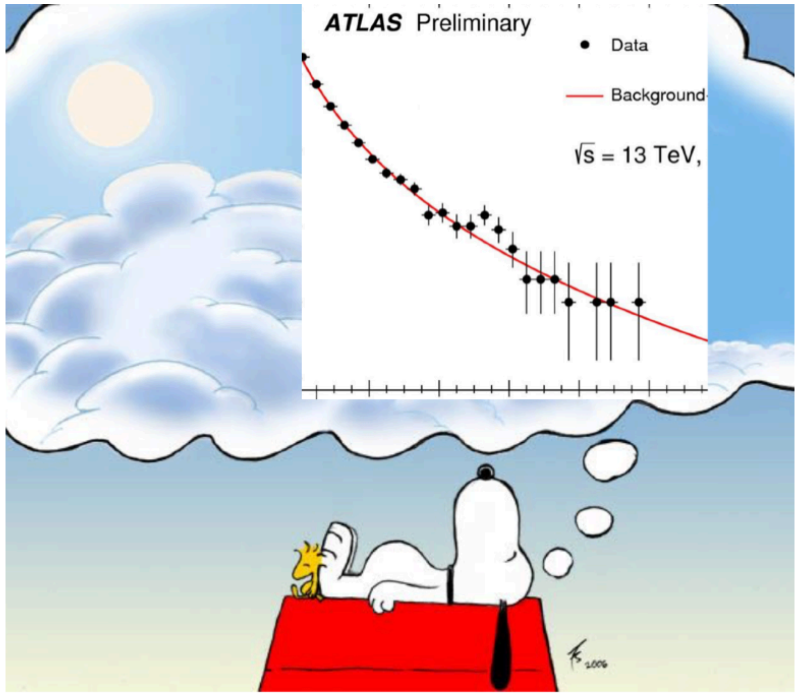
- **ALPs** at the **LHC** are theoretically well motivated (e.g. heavy **QCD axion**, SUSY **R-axion**,…)
- Existing searches do not go below 50-70 GeV mass
- But they could!

Lower masses in boosted dijet searches

We set **strongest bound on ALPs** from $\gamma\gamma$

We propose concrete new searches at **ATLAS**&**CMS**, **LHCb** and **Belle-II**

Mariotti Redigolo FS Tobioka 1710.01743
+ Cid Vidal 1810.xxxxx
+ Low in progress



- **NEXT**: LHC & Belle-II perform the actual searches!

  Other LHC (e.g. coupling with fermions)?
  Cacciapaglia+1710.11142

  <u>Lot of other Belle-II</u>

  ….

Back up

More on R-axion

PGB from SUSY: R-symmetry

N = 1 SUSY always accompanied by a continuous $U(1)_R$ = "R-symmetry"

$$R: \ \theta_\alpha \to e^{i\epsilon}\,\theta_\alpha \qquad [R, Q] = -Q$$

R-charge assignments: $$\Phi = \phi + \sqrt{2}\theta\,\psi + \theta^2\,F$$

$$r_\phi = r_\Phi$$
$$r_\psi = r_\Phi - 1$$
$$r_F = r_\Phi - 2$$

Vector superfields are real $\Rightarrow$ gauginos have $r_\lambda = 1$

Lagrangian $\mathcal{L}$ R-symmetric $\Rightarrow R(W) = 2$

($\Leftarrow$ if Kahler canonical)

$$\mathcal{L} \supset \int d^2\theta\, W + \text{c.c.}$$

W superpotential

A strongly coupled "UV" completion

Very low energy SUSY breaking F

motivated by:

Naturalness + Higgs mass Gherghetta Pomarol 1107.4697

+ LHC exclusions Buckley et al. 1610.08059

Gravitino cosmology Ibe Yanagida 1608.01610

needs a strongly coupled sector

so that $m_{\lambda^i} \sim \frac{g_i^2}{g_*^2} m_*$ OK with LHC bounds

m_*

$m_{\rm soft} \approx \frac{g^2}{g_*^2} m_*$

$m_a \approx \sqrt{\epsilon_{\not R}}\, m_*$

$m_G = \frac{F}{\sqrt{3} M_{Pl}}$

m_* mass gap of the hidden sector (e.g. mass of messengers in gauge mediation)

$g_* > 1$ coupling between hidden sector states

SUSY Naive Dimensional Analysis

$M_{\rm SUSY} \sim m_* \sim g_* f \qquad f_a \sim f$

$F \sim g_* f^2 \qquad w_R \sim g_* f^3$

inspired by Cohen et al. 1997, Luty 1998, Giudice+ 2007

$a \to GG$ saturates the upper bound

The R-axion pheno Lagrangian-I

Komargodski Seiberg 0907.2441

Tool: constrained superfield formalism

$$X = \frac{G^2}{2\,F_X} + \sqrt{2}\theta\, G + \theta^2\, F_X$$

satisfy the constraints $\begin{cases} X^2 = 0 \\ X(R^\dagger R - 1) = 0 \end{cases}$

$$\mathcal{R} = e^{i\mathcal{A}/f_a} = e^{ia/f_a + O(a\,G,\ldots)}$$

~ analogous to ordinary Goldstones $U^\dagger U = 1 \quad U = e^{i\pi}$

Most general effective Lagrangian: $r_X = 2 \quad r_\mathcal{R} = 1$

$$\mathcal{L}_{G+a} = \int d^4\theta\,(X^\dagger X + f_a^2 \mathcal{R}^\dagger \mathcal{R}) + \int d^2\theta\,(FX + w_R \mathcal{R}^2) + \text{c.c.}$$

Absent for any other axion

$$-\frac{w_R}{f_a\, F^2}\Box a\, \bar{G} i\gamma_5 G$$

First pheno prediction (valid for any UV completion!):

R-axion decays to missing energy

$$w_R < \frac{1}{2} f_a F$$

$$\Gamma_{a\to GG} < \frac{1}{32\pi}\frac{m_a^5}{F^2}$$

Dine Festuccia Komargodski 0910.2527
see also Bellazzini 1605.06111

R-axion pheno overview

Tool: constrained superfield formalism

Komargodski Seiberg 0907.2441

$$X = \frac{G^2}{2\,F_X} + \sqrt{2}\theta\, G + \theta^2\, F_X$$

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$$\mathcal{R} = e^{i\mathcal{A}/f_a} = e^{ia/f_a} + O(a\,G, \ldots)$$

~ analogous to ordinary Goldstones $U^\dagger U = 1 \quad U = e^{i\pi}$

$r_\mathcal{R} = 1 \quad r_X = 2 \quad r_\mathcal{W} = 1$

$$\mathcal{L}_{\text{gauge}} = \int d^2\theta \left(\frac{1}{4} - i g_i^2 \frac{c_i^{\text{hid}}}{16\pi^2}\mathcal{A}\right)\mathcal{W}_i^2 - \int d^2\theta \frac{m_{\lambda_i}}{2F} X \mathcal{R}^{-2}\mathcal{W}_i^2 + \text{c.c.}$$

$$\frac{g_i^2 c_i^{\text{hid}}}{16\pi^2}\frac{a}{f_a}F^i\tilde{F}^i$$

$$g_i^2\frac{c_i^{\text{eff}}}{16\pi^2}\frac{\partial_\mu a}{f_a}\bar{\lambda}_i\gamma_\mu\gamma_5\lambda_i - i\frac{m_{\lambda_i}}{f_a}a\,\bar{\lambda}_i\gamma_5\lambda_i$$

$R_H \equiv r_{H_u} + r_{H_d}$

$$\mathcal{L}_{\text{Higgs}} \supset \int d^4\theta \left(\frac{\mu}{F}X^\dagger H_u H_d \mathcal{R}^{2-R_H} - \frac{B_\mu}{F^2}X^\dagger X H_u H_d \mathcal{R}^{-R_H} + \text{c.c}\right)$$

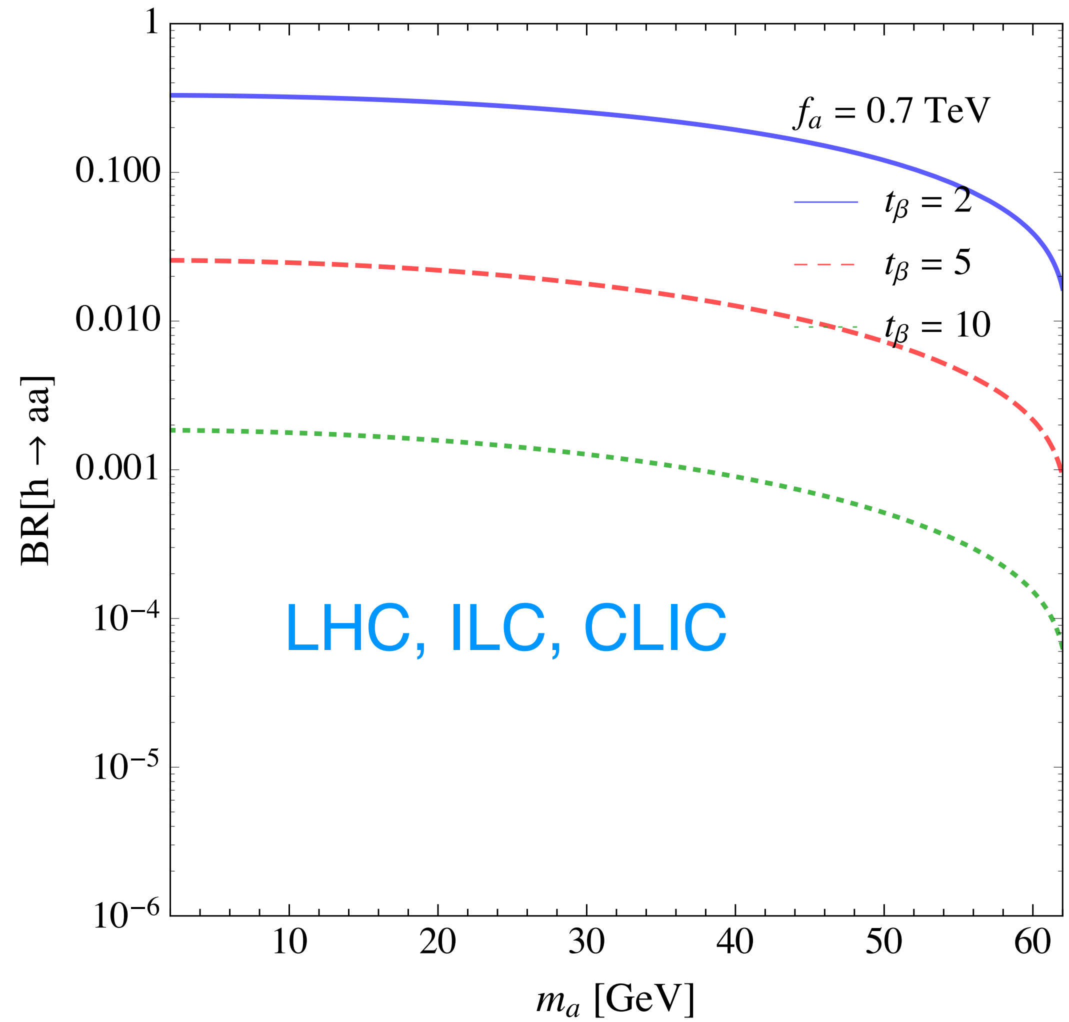
$$-i\,a\,R_H\left(c_\beta^2\frac{m_u}{f_a}\bar{u}\gamma_5 u + s_\beta^2\frac{m_d}{f_a}\bar{d}\gamma_5 d + s_\beta^2\frac{m_\ell}{f_a}\bar{\ell}\gamma_5\ell\right)$$

$$\frac{\delta^2}{v}(\partial_\mu a)^2 h \qquad \delta = R_H\frac{v}{f_a}\frac{s_{2\beta}}{2}$$

a from decays of h, Υ and B

$$\mathcal{L}_{ha^2} = \frac{\delta^2}{v}(\partial_\mu a)^2 h$$

$$\delta = R_H \frac{v}{f_a}\frac{s_{2\beta}}{2}$$



$$\mathrm{BR}_{\Upsilon\to\gamma\, a} \simeq 3-5\times 10^{-5}\left(\frac{\mathrm{TeV}}{f_a}\right)^2$$

since Wilczek PRL39 (1977)

experiments: BABAR

Belle-II

$$\mathrm{BR}_{B\to K a,\, K^* a} \simeq 3-5\times 10^{-4}\left(\frac{\mathrm{TeV}}{f_a}\right)^2$$

LHCb

Belle, Belle-II

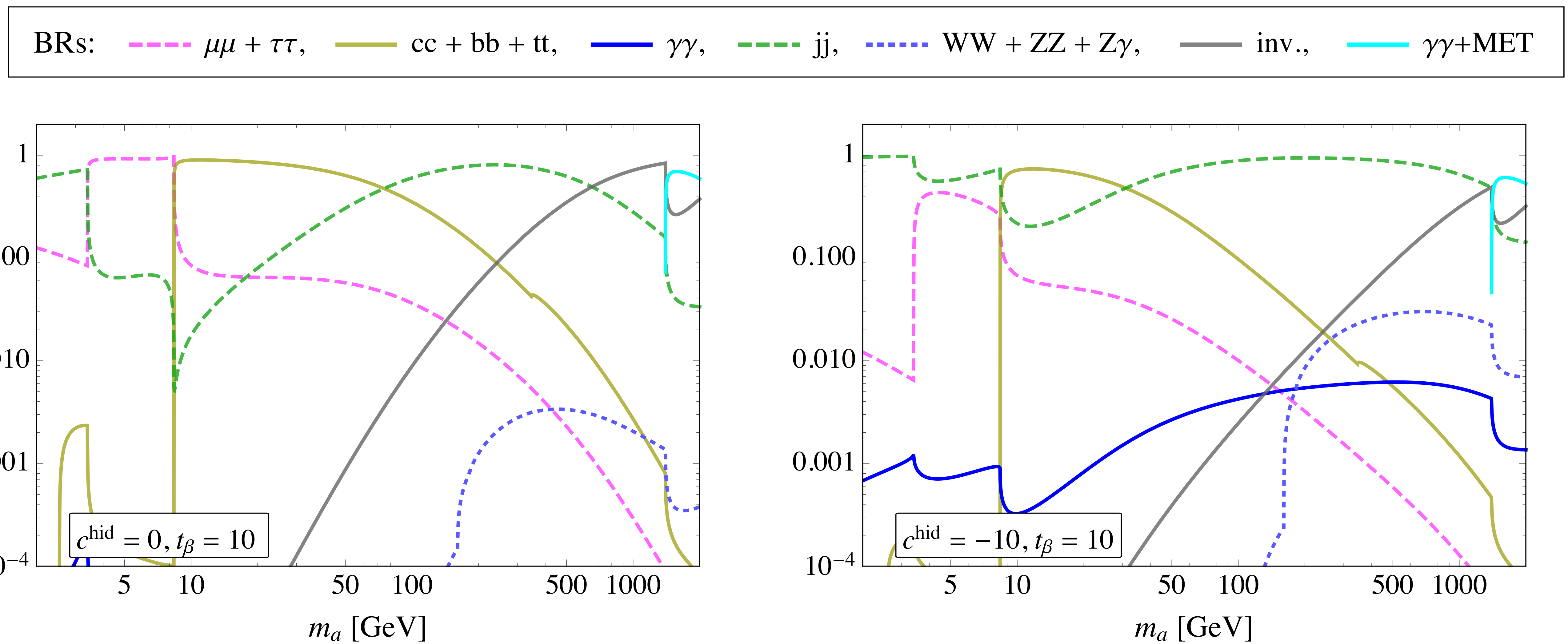
see Hall Wise 1981, Freytsis Ligeti Thaler 0911.5355

R axion branching ratios

Both plots: $t_\beta = 10$

No anomaly

Large anomalies

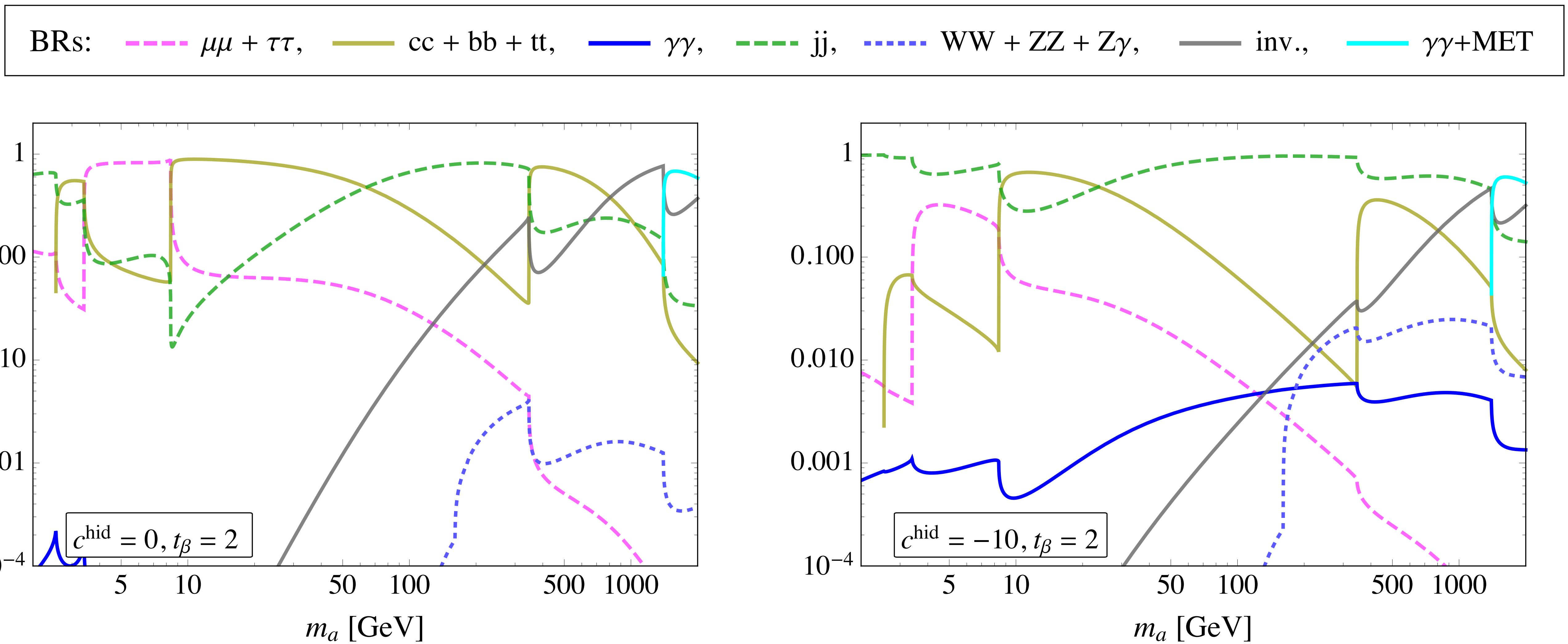


R axion branching ratios

Both plots: $t_\beta = 2$

No anomaly

Large anomalies



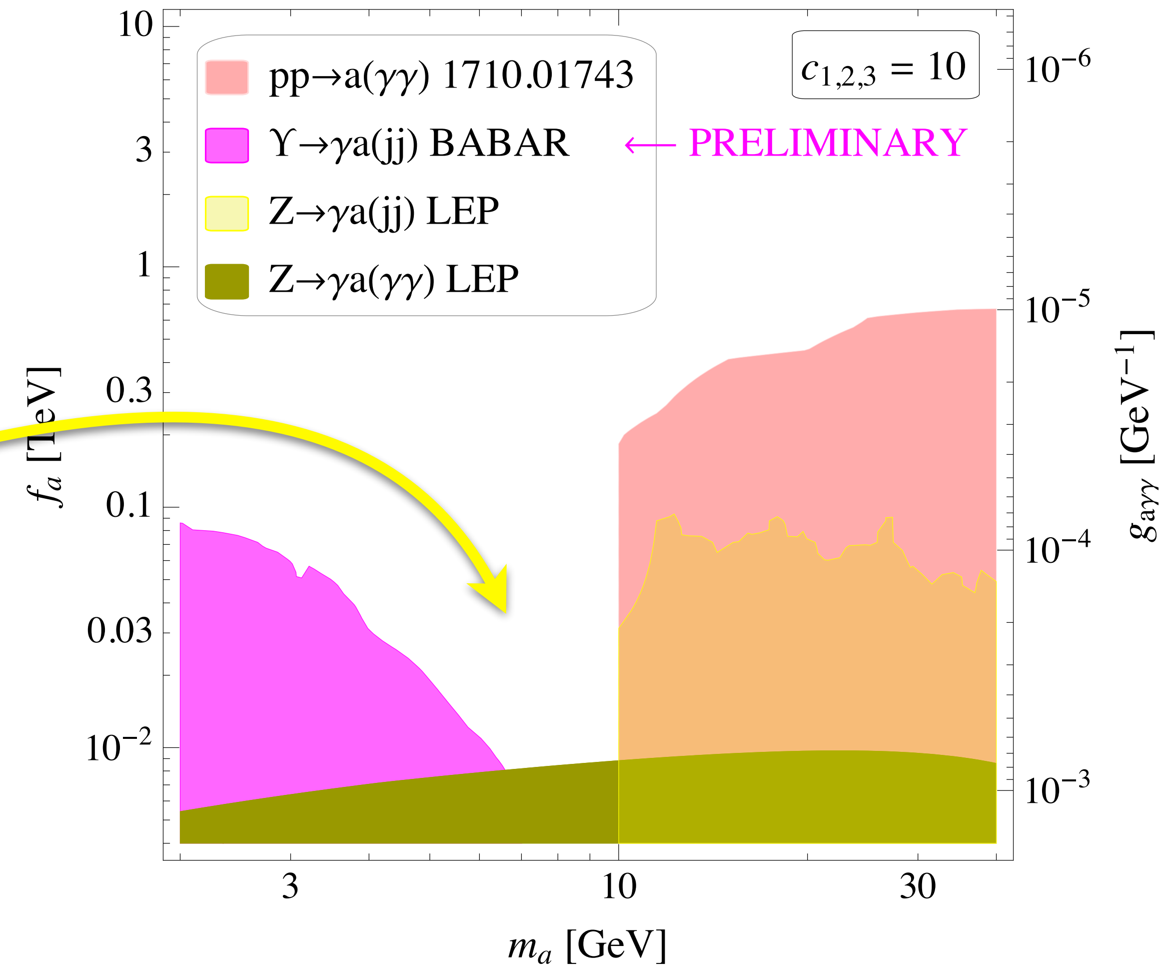
More on low-mass $\gamma\gamma$

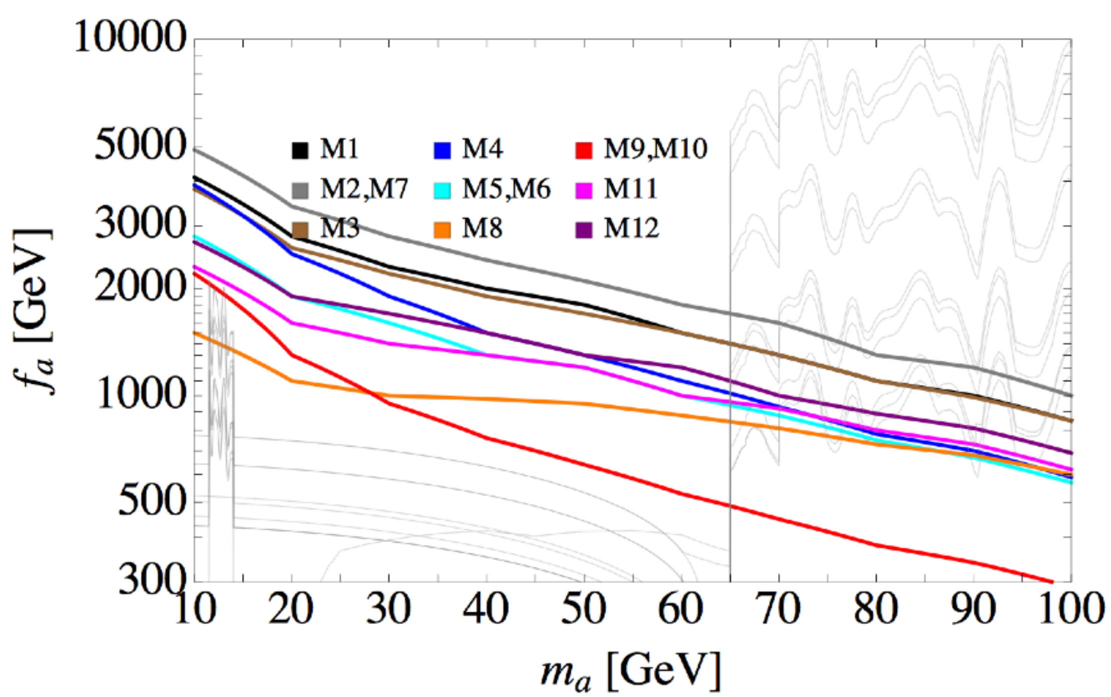
Other ways to low-mass resonances?

$m_{\gamma\gamma} < 10$ GeV at the LHCb?

work in progress…

Big hole for $4 \text{ GeV} \lesssim m_a \lesssim 10 \text{ GeV}$





Difermions, e.g. ditaus?

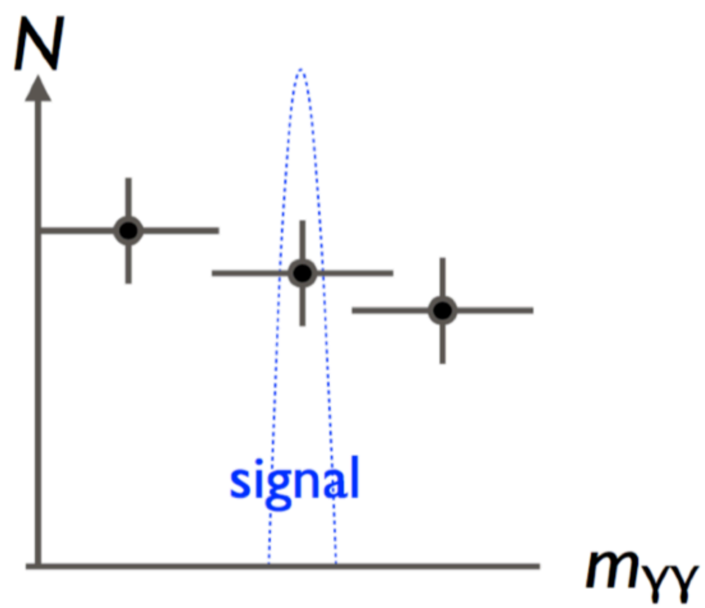
Cacciapaglia Ferretti Flacke Serodio 1710.11142

NB. sensitivities not based on data

definitely worth investigating

New $\gamma\gamma$ Bound & Sensitivities

Starting point: inclusive **diphoton cross section measurements** @ ATLAS7,8 and CMS7



1. **New Bound** we assume zero knowledge of bkg

$$N_{\rm bin}^{\rm signal} < N_{\rm bin}^{\rm meas.}(1 + 2\,\Delta_{\rm bin})$$

experimental rel. uncertainty

2. **Reach** we assume data = SM prediction

$$N_{\rm bin}^{\rm signal} < N_{\rm bin}^{\rm meas.} \times 2\,\Delta_{\rm bin}$$

3. **Reach** with smarter bins (= **2.**, where we reduce ~ 10 GeV bins to mass resolution of ~ 3 GeV)

4. **Reach** we simulate bkg with same cuts at different energies [Madgraph+Pythia+Delphes]

$$N_{\rm bin}^{\rm signal}(E_{\rm high}) < N_{\rm bin}^{\rm signal}(E_{\rm low}) \cdot \sqrt{\frac{L_{\rm high}}{L_{\rm low}} \cdot \frac{\sigma_{\rm high}^{\rm MC}}{\sigma_{\rm low}^{\rm MC}}}$$

Reach of **3.** Simulated bkg cross sections

Low-mass analyses we found

Experiment	Process	Lumi	$\sqrt{s}$	low mass reach	ref.
LEPI	$e^+e^- \to Z \to \gamma a \to \gamma jj$	12 pb^{-1}	Z-pole	10 GeV	[29]
LEPI	$e^+e^- \to Z \to \gamma a \to \gamma\gamma\gamma$	78 pb^{-1}	Z-pole	3 GeV	[30]
LEPII	$e^+e^- \to Z^*, \gamma^* \to \gamma a \to \gamma jj$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[31]
LEPII	$e^+e^- \to Z^*, \gamma^* \to \gamma a \to \gamma\gamma\gamma$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[31, 32]
LEPII	$e^+e^- \to Z^*, \gamma^* \to Za \to jj\gamma\gamma$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[31]
D0/CDF	$p\bar{p} \to a \to \gamma\gamma$	7/8.2 fb^{-1}	1.96 TeV	100 GeV	[33]
ATLAS	$pp \to a \to \gamma\gamma$	20.3 fb^{-1}	8 TeV	65 GeV	[34]
CMS	$pp \to a \to \gamma\gamma$	19.7 fb^{-1}	8 TeV	80 GeV	[35]
CMS	$pp \to a \to \gamma\gamma$	19.7 fb^{-1}	8 TeV	150 GeV	[36]
CMS	$pp \to a \to \gamma\gamma$	35.9 fb^{-1}	13 TeV	70 GeV	[37]
CMS	$pp \to a \to jj$	18.8 fb^{-1}	8 TeV	500 GeV	[38]
ATLAS	$pp \to a \to jj$	20.3 fb^{-1}	8 TeV	350 GeV	[39]
CMS	$pp \to a \to jj$	12.9 fb^{-1}	13 TeV	600 GeV	[40]
ATLAS	$pp \to a \to jj$	3.4 fb^{-1}	13 TeV	450 GeV	[41]
CMS	$pp \to ja \to jjj$	35.9 fb^{-1}	13 TeV	50 GeV	[42]
UA2	$p\bar{p} \to a \to \gamma\gamma$	13.2 pb^{-1}	0.63 TeV	17.9 GeV	[43]
D0	$p\bar{p} \to a \to \gamma\gamma$	4.2 fb^{-1}	1.96 TeV	8.2 GeV	[44]
CDF	$p\bar{p} \to a \to \gamma\gamma$	5.36 fb^{-1}	1.96 TeV	6.4 GeV	[45, 46]
ATLAS	$pp \to a \to \gamma\gamma$	4.9 fb^{-1}	7 TeV	9.4 GeV	[8]
CMS	$pp \to a \to \gamma\gamma$	5.0 fb^{-1}	7 TeV	14.2 GeV	[10]
ATLAS	$pp \to a \to \gamma\gamma$	20.2 fb^{-1}	8 TeV	13.9 GeV	[9]

Signal efficiencies and cross section

$$\epsilon_S(m_a) = \frac{\sigma^{\rm MCcuts}_{\gamma\gamma}(m_a,s)}{C_s\,\sigma^{\rm LO}_{\gamma\gamma}(m_a,s)}$$

$\sigma^{\rm MCcuts}_{\gamma\gamma}$ Simulated w/Madgraph+Pythia+Delphes matched up to 2 extra jets

$\sigma^{\rm LO}_{\gamma\gamma}$ reproduces up to a constant factor C_s the shape of $\sigma^{\rm MCtot}_{\gamma\gamma}$ for $m_{\gamma\gamma} \gtrsim 60$ GeV (i.e. sufficiently far from the sum of the minimal detector p_T cuts on the photons). A constant factor $C_s \equiv \sigma^{\rm MCtot}_{\gamma\gamma}(s)/\sigma^{\rm LO}_{\gamma\gamma}(s)$ is hence included in Eq. (5) and we obtain $C_{7\,\rm TeV} \simeq C_{8\,\rm TeV} \simeq 0.85$ while $C_{2\,\rm TeV} \simeq 1$ at the Tevatron center of mass energy. The

$$\sigma^{\rm th}_{\gamma\gamma}(m_a,s) = \frac{K_\sigma}{K_g}\cdot\sigma^{\rm LO}_{\gamma\gamma}(m_a,s)\,, \qquad \text{(A1)}$$

where we work in the approximation $\Gamma_{\rm tot} \simeq \Gamma_{gg}$ (which is excellent in the parameter space that we have studied), and where

$$\sigma^{\rm LO}_{\gamma\gamma}(m_a,s) = \frac{1}{m_a s}C_{gg}(m_a^2/s)\cdot\Gamma_{\gamma\gamma}\,, \qquad \text{(A2)}$$

$$C_{gg} = \frac{\pi^2}{8}\int_{m_a^2/s}^{1}\frac{dx}{x}f_g(x)f_g(\frac{m_a^2}{sx})\,, \qquad \text{(A3)}$$

where $f_g(x)$ is the gluon PDF from the `MSTW2008nnlo68` set [58], where we fix the pdf scale $q = m_a$. We work with

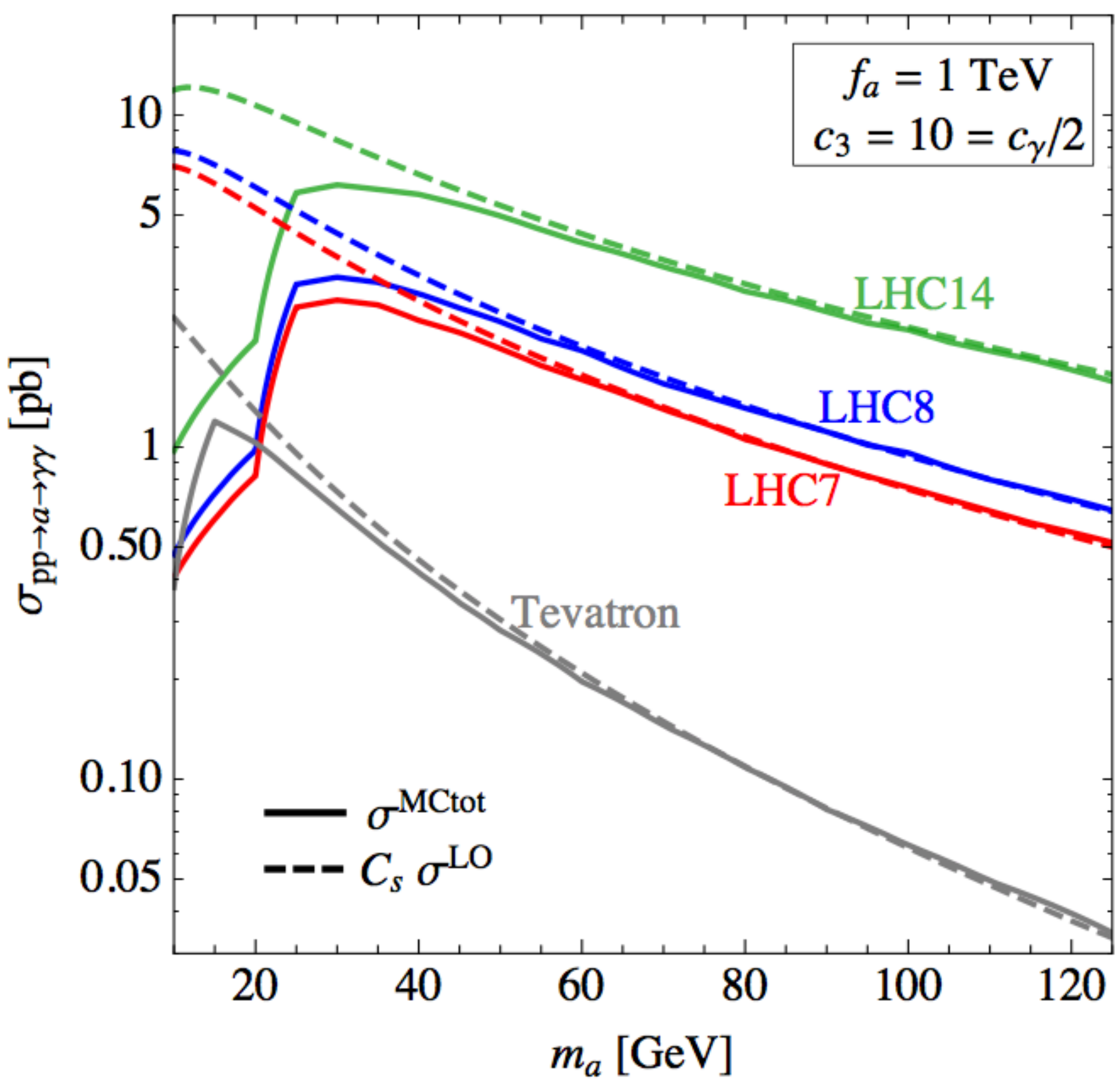
$K_\sigma = 3.7$ from ggHiggs v3.5

Bonvini et al. 2013-2016

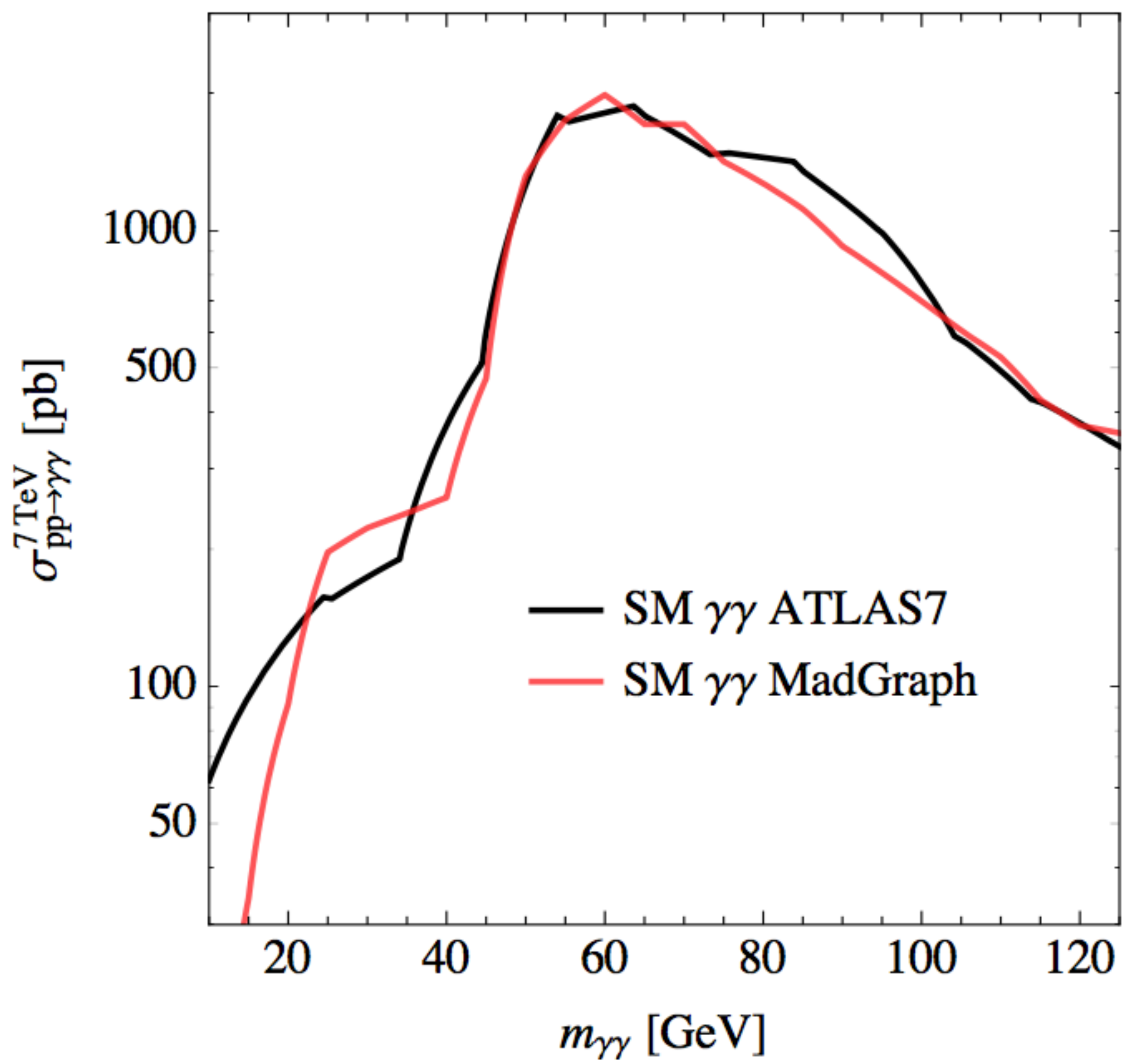
$K_g = 2.1$

m_a in GeV	10	20	30	40	50	60	70	80	90	100	110	120
ϵ_S for $\sigma_{7\rm TeV}$ ATLAS [8]	0	0.008	0.022	0.040	0.137	0.293	0.409	0.465	0.486	0.533	0.619	0.637
ϵ_S for $\sigma_{7\rm TeV}$ CMS [10]	0	0.002	0.010	0.020	0.030	0.058	0.156	0.319	0.424	0.499	0.532	0.570
ϵ_S for $\sigma_{8\rm TeV}$ ATLAS [9]	0	0.0007	0.008	0.014	0.024	0.037	0.071	0.233	0.347	0.419	0.452	0.484
ϵ_S for $\sigma_{2\rm TeV}$ CDF [45, 46]	0.001	0.007	0.026	0.143	0.212	0.241	0.276	0.275	0.283	0.3	0.319	0.327
ϵ_S for $\sigma_{2\rm TeV}$ D0 [44]	0	0.002	0.008	0.018	0.114	0.169	0.208	0.21	0.217	0.234	0.244	0.252

Validation

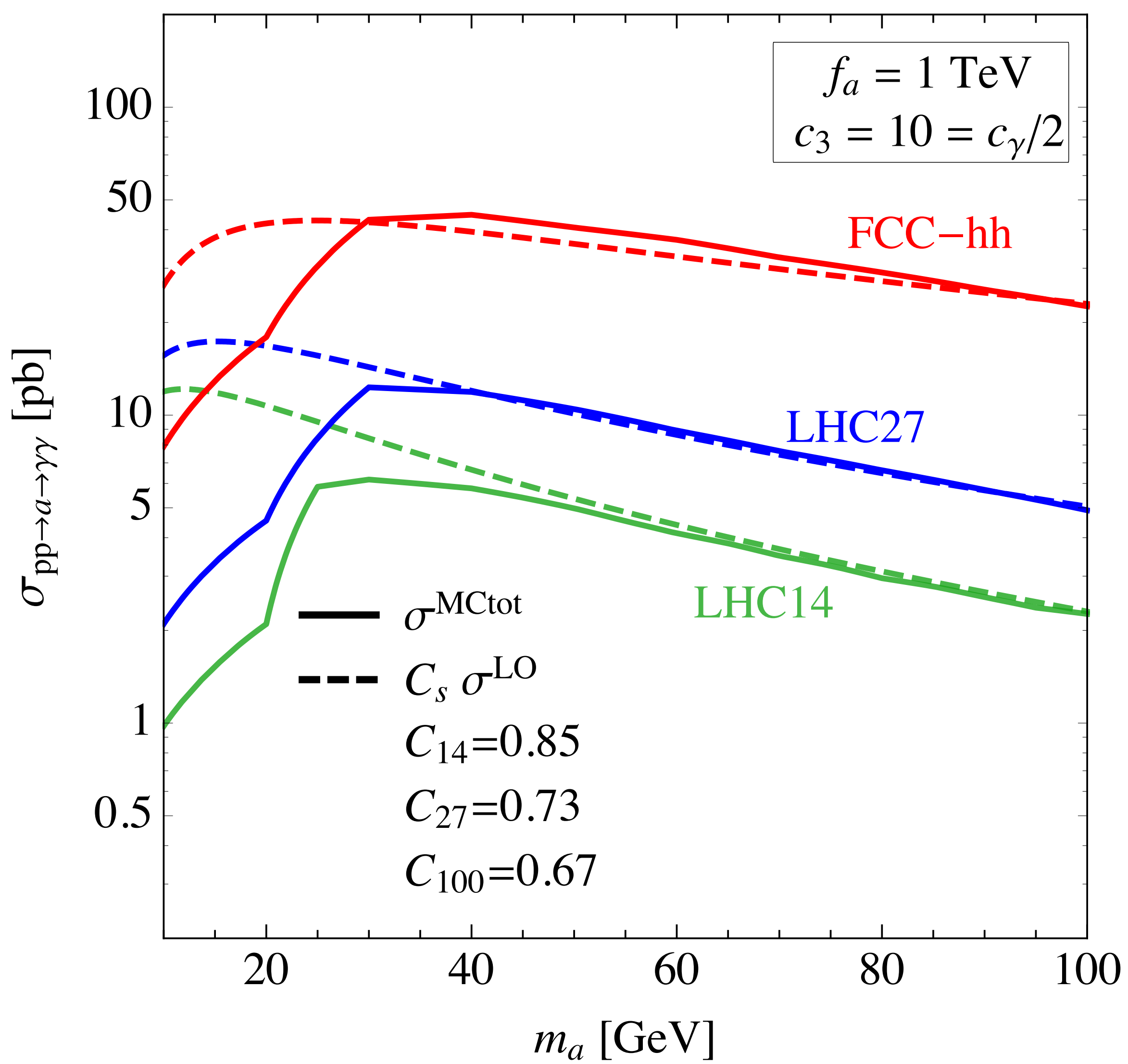


$f_a = 1$ TeV
$c_3 = 10 = c_\gamma/2$
LHC14
LHC8
LHC7
Tevatron
$\sigma^{\rm MCtot}$
$C_s\, \sigma^{\rm LO}$
$\sigma_{pp\to a\to\gamma\gamma}$ [pb]
10
5
1
0.50
0.10
0.05
20
40
60
80
100
120
m_a [GeV]



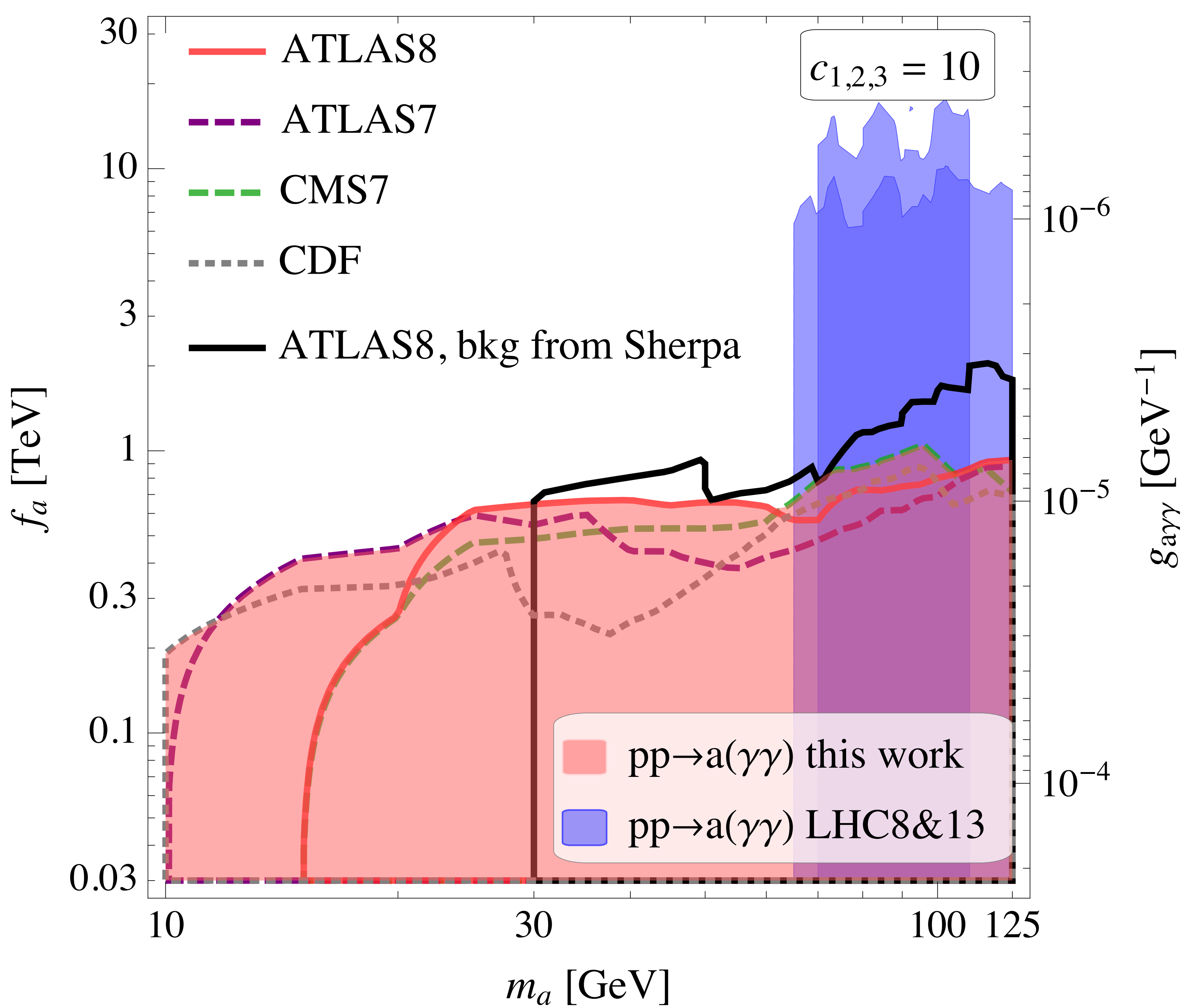
$\sigma^{7\,\rm TeV}_{pp\to\gamma\gamma}$ [pb]
1000
500
100
50
SM $\gamma\gamma$ ATLAS7
SM $\gamma\gamma$ MadGraph
20
40
60
80
100
120
$m_{\gamma\gamma}$ [GeV]

Validation



f_a = 1 TeV
$c_3 = 10 = c_\gamma/2$
FCC−hh
LHC27
LHC14
$\sigma^{\rm MCtot}$
$C_s\ \sigma^{\rm LO}$
C_{14}=0.85
C_{27}=0.73
C_{100}=0.67
$\sigma_{pp\to a\to\gamma\gamma}$ [pb]
m_a [GeV]
100
50
10
5
1
0.5
20
40
60
80
100

Interplay of LHC and Tevatron

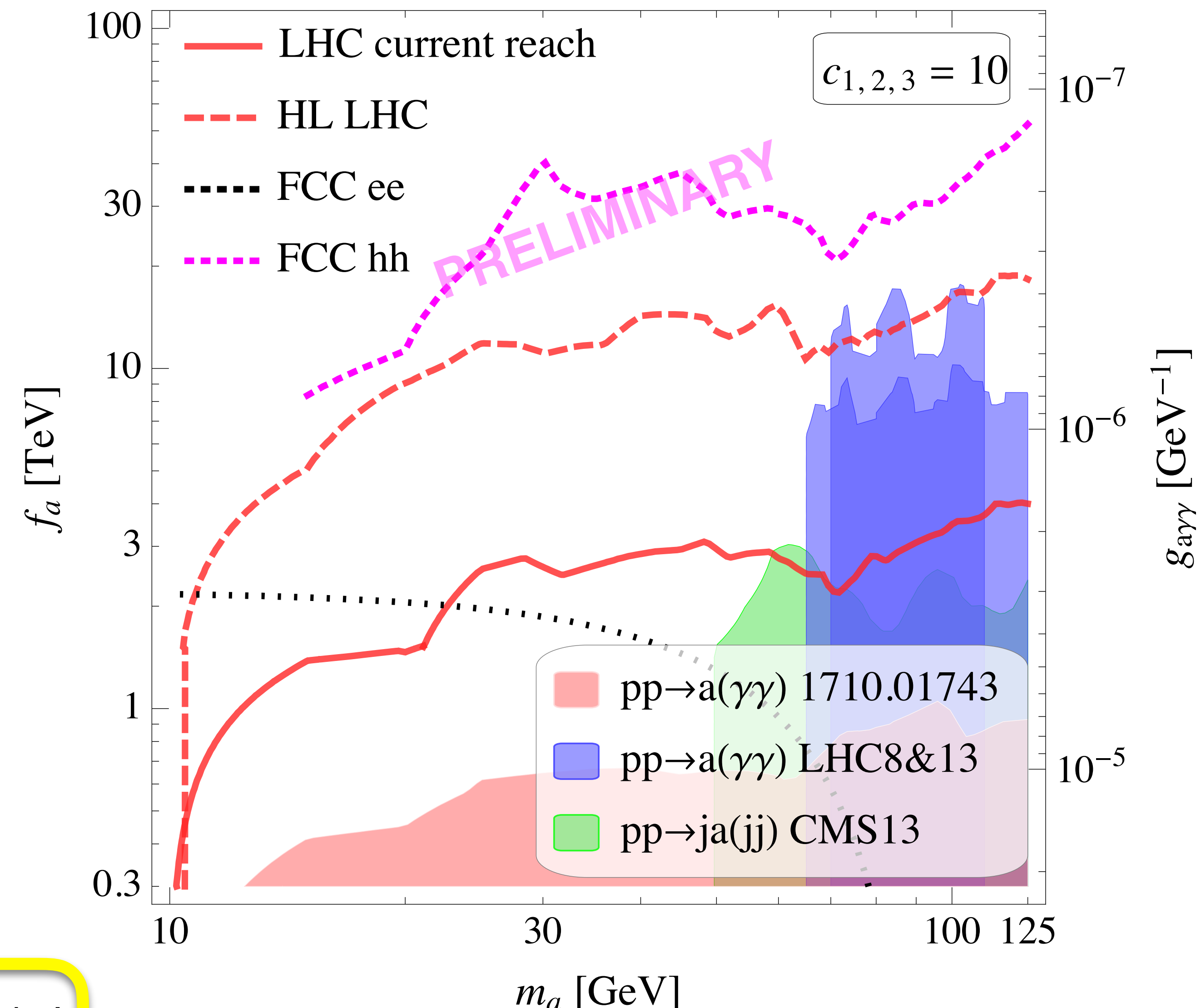


FCC

Mariotti Redigolo FS Tobioka in progress

FCC ee reach computed rescaling LEP limits on $\mathrm{BR}[Z \to \gamma a(jj)]$ and assuming 10^{12} Z bosons

If $aG\tilde{G}$ switched on HL-LHC wins over FCC ee



FCC hh reach computed like LHC14 one [4., from simulations, Lumi= $3\ \mathrm{ab}^{-1}$]

NB. pT cuts as in ATLAS8 (30, 40 GeV)

Still, speculative even for FCC standards!

this search has not even been performed at 8 TeV

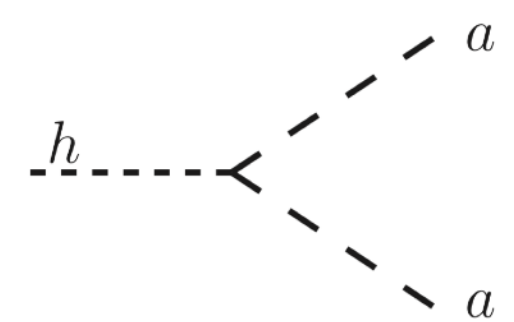
at 100 TeV game could be very different (larger boosts,…)

Thoughts in progress…

ALPs without gluons

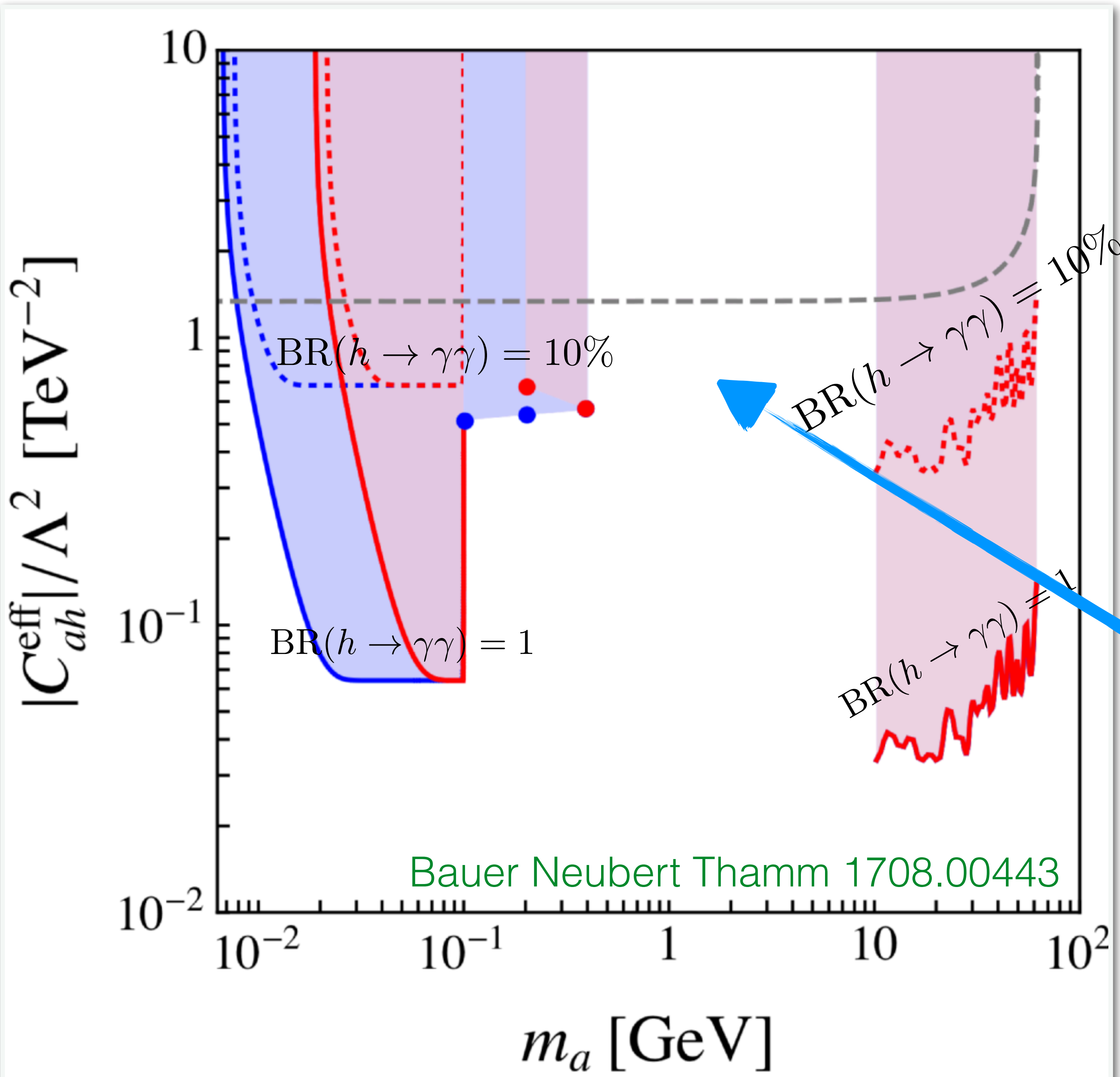
LHC & other ALP couplings (no gluons)

A selected example: **Higgs decays** to 4 photons



$$\mathcal{L}_{\rm eff}^{D\geq 6} = \frac{C_{ah}}{\Lambda^2} (\partial_\mu a)(\partial^\mu a)\, \phi^\dagger \phi$$

$$\mathcal{L}_{\rm eff}^{D\leq 5} \ni e^2\, C_{\gamma\gamma}\, \frac{a}{\Lambda}\, F_{\mu\nu}\, \tilde{F}^{\mu\nu}$$



Modified Diphoton Isolation could help fill this gap?

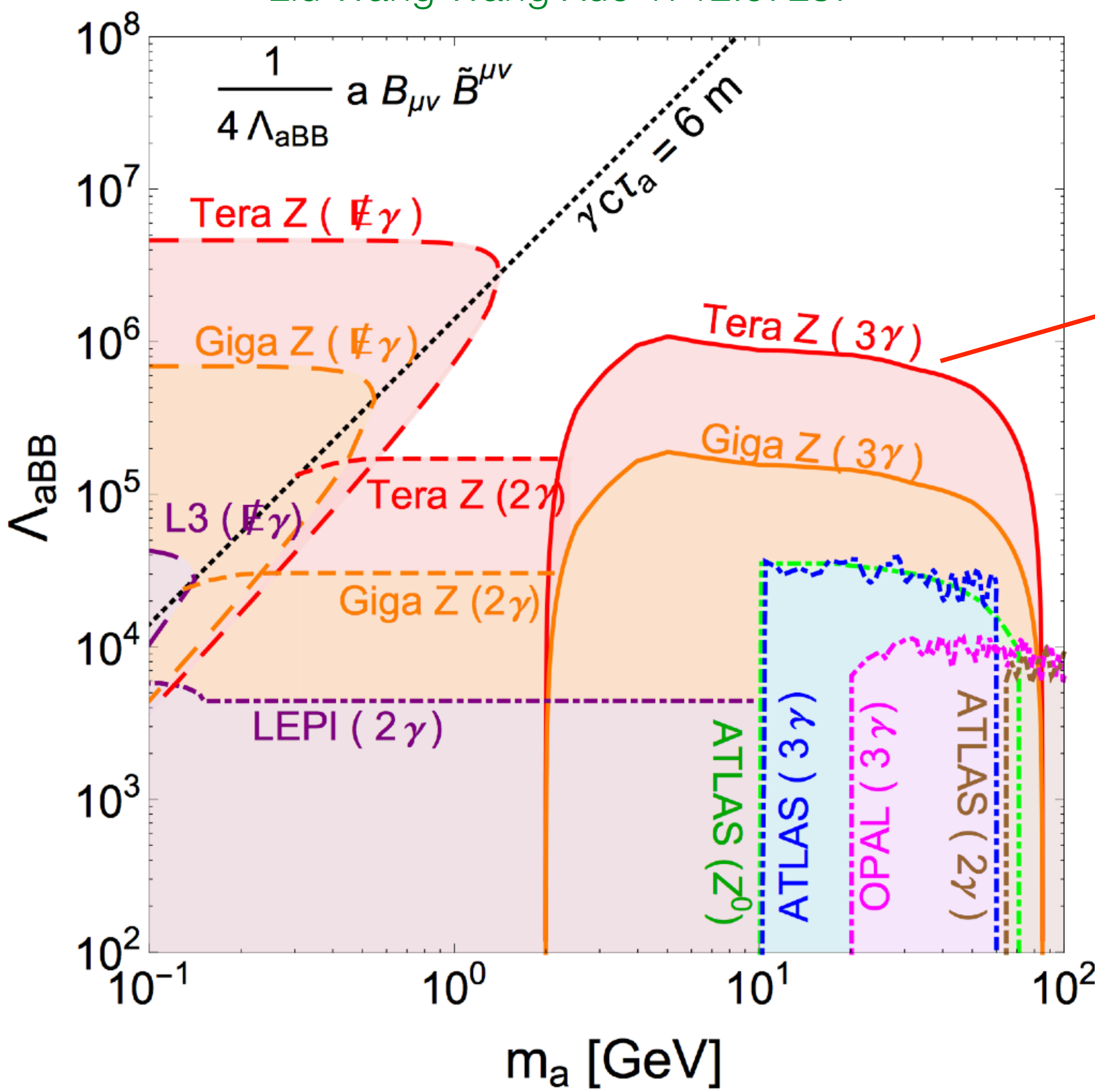
For more on ALP at colliders see e.g.

Mimasu Sanz 1409.4792, ,,,,, Bauer+1808.10323

FCC-ee with no gluon coupling

$$\mathcal{L}_{\rm int} = \frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right] \qquad \alpha_1 = \tfrac{5}{3}\alpha_y$$

Liu Wang Wang Xue 1712.07237



To compare with previous slides:

$$\Lambda_{\rm aBB} = \frac{\pi}{c_1\,\alpha_1} f_a \simeq 20\, f_a \frac{10}{c_1}$$

For Tera Z $\mathrm{BR}[Z \to \gamma a(\gamma\gamma)] \lesssim 3\times 10^{-9}$

[current LEP limit $\lesssim 5\times 10^{-6}$]

FCC ee could reach $f_a \lesssim 100$ TeV

FCC hh VBF ?

Associated production ?

Photon fusion ?

???